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GELS FOR ENCAPSULATION OF BIOLOGICAL MATERIALS

This application is a Continuation of 08/510,089, filed August 1, 1995, which is a CIP of 07/958,870, filed 10/7/92, 15 which is a CIP of 07/870,540 (abandoned), filed 4/20/92; this is also a CIP of 08/379,848, filed 1/27/95, which is a continuation of 08/022,687 filed 3/1/93 and issued as U.S.P.N. 5,410,016, which is a CIP of 07/843,485, filed 2/28/92 (abandoned); this is also a CIP of 08/336,393, filed 11/10/94, which is a 20 continuation of 07/598,880, filed 10/15/90 (abandoned.)

BACKGROUND

Microencapsulation technology holds promise in many areas of medicine. For example, some important applications are treatment of diabetes (Goosen, M. F. A., et al. (1985) 25 Biotechnology and Bioengineering, 27:146.), production of biologically important chemicals (Omata, T., et al. (1979) European J. Appl. Microbiol. Biotechnol., 6:207:215), evaluation of anti-human immuno-deficiency virus drugs (McMahon, J., et al., (1990) J. Nat. Cancer Inst., 82(22) 1761-1765), 30 encapsulation of hemoglobin for red blood cell substitutes, and controlled release of drugs. During encapsulation using prior methods, cells are often exposed to processing conditions which are potentially cytotoxic. These conditions include heat, organic solvents and

5

TABLE 6

Gel strength Tests

	PEO Acrylate Precursor Molecular Weight			
	0.4 kD	6 kD	10 kD	18.5 kD
Stress (kPa)*	168+/-51	98+/-15	33+/-7	115+/-56
% Strain*	8+/-3	71+/-13	110+/-9	40+/-15
Slope*	22+/-5	1.32+/-0.31	0.27+/-0.04	2.67+/-0.55

*Values are mean+/-S.D.

For the creep tests, eight samples approximately 0.2 X 0.4 X 2 cm were loaded while submersed in saline solution. They were tested with a constant unique predetermined load for one hour and a small recovery load for ten minutes. Gels made from PEG diacrylates of 1 kD, 6 kD, and 10 kD, and PEG tetraacrylates of 18.5 kD PEO molecular weight were used for this study. The 10 kD test was terminated due to a limit error (the sample stretched beyond the travel of the loading frame). The 1 kD sample was tested with a load of 10g and a recovery load of 0.2g. The 6 kD sample was tested at a load of 13g with a recovery load of 0.5g. The 18.5 kD sample was tested at a load of 13g with a recovery load of 0.2g. The choice of loads for these samples produced classical creep curves with primary and secondary regions. The

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5 traces for creep for the 1 kD, 6 kD, and 18.5 kD samples appear
in Figure 14A-C, respectively.

Example 20

Water Content of PEO Gels

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10 Solutions of various macromers were made as described
above. Gels in the shape of discs were made using a mold. The
solutions (400 μ L) was used for each disc. The solutions were
irradiated for 2 minutes to ensure thorough gelation. The disc
shaped gels were removed and dried under vacuum at 60°C for 2
days. The discs were weighed (W1) and then extracted repeatedly
15 with chloroform for 1 day. The discs were dried again and
weighed (W2). The gel fraction was calculated as $W2/W1$. This
data appears in Table 7.

Determination of Degree of Hydration

20 Subsequent to extraction, the discs were allowed to
equilibrate with HBS for 6 hours and weighed (W3) after excess
water had been carefully swabbed away. The total water content
was calculated as $(W3-W2) \times 100/W3$. The data for gel water
contents is summarized in the following table.

5

TABLE 7

Polymer Coat	% Total Water	% Gel Content
0.4 kD	-	99.8 ± 1.9
1 kD	79.8 ± 2.1	94.5 ± 2.0
6 kD	95.2 ± 2.5	69.4 ± 0.6
10 kD	91.4 ± 1.6	96.9 ± 1.5
18.5 kD	91.4 ± 0.9	80.3 ± 0.9
20 kD	94.4 ± 0.6	85.0 ± 0.4

10

Example 21

Mechanical Stability of PEO Gels after Implantation

15

PEG diacrylate (10 kD) and PEG tetraacrylate (18.5 kD) were cast in dogbone shapes as described in Example 19. PEG-- diacrylate or tetraacrylate (23% w/w) in sterile HEPES buffered saline (HBS) (0.9% NaCl, 10 - HEPES, pH 7.4) containing 900 ppm of 2,2-dimethoxy-2-phenoxyacetophenone as initiator, was poured into an aluminum mold and irradiated with a LWUV lamp (Black ray) for 1 min. The initial weights of these samples were found after oven-drying these gels to constant weight. The samples were soxhlet-extracted with methylene chloride for 36 hours in order to leach out any unreacted prepolymer from the gel matrix (sol-leaching) prior to testing. The process of extraction was continued until the dried gels gave constant weight.

20

25

ICR Swiss male white mice, 6-8 weeks old (Sprague-Dawley), were anesthetized by an intraperitoneal injection of

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5 sodium pentobarbital. The abdominal region of the mouse was
shaved and prepared with betadine. A ventral midline incision
10-15 mm long was made. The polymer sample, fully hydrated in
sterile PBS (Phosphate buffered saline) or HEPES buffered saline
(for calcification studies), was inserted through the incision
10 and placed over the mesentery, away from the wound site. The
peritoneal wall was closed with a lock stitched running suture
(4.0 silk, Ethicon). The skin was closed with stainless steel
skin staples, and a topical antibiotic (Furacin) was applied over
the incision site. Three animals were used for each time point.
15 One dogbone sample was implanted per mouse and explanted at the
end of 1 week, 3 weeks, 6 weeks, and 8 weeks. Explanted gels
were rinsed in HBS twice and then treated with 0.3 mg/mL pronase
(Calbiochem) to remove any adherent cells and tissue. The
samples were then oven-dried to a constant weight, extracted, and
20 reswelled as mentioned before.

Tensile stress strain test was conducted on both
control (unimplanted) and explanted dogbones in a small
horizontal Instron-like device. The device is an aluminum
platform consisting of two clamps mounted flat on a wooden board
25 between two parallel aluminum guide. The top clamp was
stationary while the bottom clamp was movable. Both the
frictional surfaces of the moving clamp and the platform were
coated with aluminum backed Teflon (Cole-Parmer) to minimize
frictional resistance. The moving clamp was fastened to a device

5 capable of applying a gradually increasing load. The whole set up
was placed horizontally under a dissecting microscope (Reichert)
and the sample elongation was monitored using a video camera.
The image from the camera was acquired by an image processor
(Argus-10, Hamamatsu) and sent to a monitor. After breakage, a
10 cross section of the break surface was cut and the area measured.
The load at break was divided by this cross section to find the
maximum tensile stress. Table 8 lists the stress at fracture of
PEG tetraacrylate (18.5 kD) hydrogels explanted at various time
intervals. No significant change in tensile strength was evident
15 with time. Thus, the gels appear mechanically stable to
biodegradation in vivo within the maximum time frame of implant
in mice.

TABLE 8

	TIME	STRESS (KPa)	STRAIN AV.
20	IMPLANTED	(mean \pm error*)	(mean \pm error*)
	1 WK	52.8 \pm 16.7	0.32 \pm 0.19
	3 WK	36.7 \pm 10.6	0.37 \pm 0.17
	6 WK	73.3 \pm 34.9	0.42 \pm 0.26
	8 WK	34.1†	0.30†
25	CONTROL	44.9 \pm 5.3	0.22 \pm 0.22

* Error based on 90% confidence limits.

† Single sample.

5

Example 22

Monitoring of Calcification of PEO Gels

Disc shaped PEG-tetraacrylate hydrogels (m.w. 18.5 kD) were implanted intraperitoneally in mice as mentioned above for a period of 1 week, 3 weeks, 6 weeks, or 8 weeks. Explanted gels were rinsed in HBS twice and treated with Pronase (Calbiochem) to remove cells and cell debris. The samples were then equilibrated in HBS to let free Ca^{++} diffuse out from the gel matrix. The gels were then oven-dried (Blue-M) to a constant weight and transferred to Aluminum oxide crucibles (COORS, high temperature resistant). They were incinerated in a furnace at 700°C for at least 16 hours. Crucibles were checked for total incineration, if any residual remnants or debris was seen they were additionally incinerated for 12 hours. Subsequently, the crucibles were filled with 2 mL of 0.5 M HCl to dissolve Ca^{++} salt and other minerals in the sample. This solution was filtered and analyzed with atomic absorption spectroscopy (AA) for calcium content.

Calcification data on PEG-tetraacrylate (mol. wt. 18.5 kD) gel implants is given in Table 9. No significant increase in calcification was observed up to an 8 week period of implantation in mice.

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TABLE 9

	TIME (Days)	CALCIFICATION (mean \pm error*) (mg Calcium/g of Dry gel wt.)
	7	2.33 \pm 0.20
	21	0.88 \pm 0.009
10	42	1.08 \pm 0.30
	56	1.17 \pm 0.26

* Error based on 90% confidence limits.

Example 23

Encapsulation of Neurotransmitter-Releasing Cells

15 Paralysis agitans, more commonly called Parkinson's
disease, is characterized by a lack of the neurotransmitter
dopamine within the striatum of the brain. Dopamine secreting
cells such as cells from the ventral mesencephalon, from
neuroblastoid cell lines or from the adrenal medulla can be
20 encapsulated in a manner similar to that of other cells mentioned
in prior Examples. Cells (including genetically engineered
cells) secreting a precursor for a neurotransmitter, an agonist,
a derivative or a mimic of a particular neurotransmitter or
analogs can also be encapsulated.

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Example 24

Encapsulation of Hemoglobin for Synthetic Erythrocytes

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Hemoglobin in its free form can be encapsulated in PEG
gels and retained by selection of a PEG chain length and cross-
link density which prevents diffusion. The diffusion of
10 hemoglobin from the gels may be further impeded by the use of
polyhemoglobin, which is a cross-linked form of hemoglobin. The
polyhemoglobin molecule is too large to diffuse from the PEG gel.
Suitable encapsulation of either native or crosslinked hemoglobin
may be used to manufacture synthetic erythrocytes. The entrap-
15 ment of hemoglobin in small spheres ($< 5\mu\text{m}$) of these highly
biocompatible materials would lead to enhanced circulation times
relative to crosslinked hemoglobin or liposome encapsulated
hemoglobin.

Hemoglobin in PBS is mixed with the prepolymer in the
20 following formulation:

Hemoglobin at the desired amount

PEG DA (MW 10000) 35%

PEG DA (MW 1000) 5%

PBS 60%

25 with 2,2-dimethoxy, 2-phenyl acetophenone at 1.6% of the above
solution.

This solution is placed in mineral oil at a ratio of 1
part hemoglobin/prepolymer solution to 5 parts mineral oil and is
rapidly agitated with a motorized mixer to form an emulsion.

5 This emulsion is illuminated with a long-wavelength ultraviolet
light (360nm) for 5 min to crosslink the PEG prepolymer to form a
gel. The mw of the prepolymer may be selected to resist the
diffusion of the hemoglobin from the gel, with smaller PEG DA
molecular weights giving less diffusion. PEG DA of MW 10000,
10 further crosslinked with PEG DA 1000, should possess the
appropriate permselectivity to restrict hemoglobin diffusion, and
it should possess the appropriate biocompatibility to circulate
within the bloodstream.

Example 25

15 **Entrapment of Enzymes for Correction of
Metabolic Disorders and Chemotherapy**

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20 Congenital deficiency of the enzyme catalase causes
acatalasemia. Immobilization of catalase in PEG gel networks
could provide a method of enzyme replacement to treat this
disease. Entrapment of glucosidase can similarly be useful in
treating Gaucher's disease. Microspherical PEG gels entrapping
urease can be used in extracorporeal blood to convert urea into
ammonia. Enzymes such as asparaginase can degrade amino acids
needed by tumor cells. Immunogenicity of these enzymes prevents
25 direct use for chemotherapy. Entrapment of such enzymes in
immunoprotective PEG gels, however, can support successful
chemotherapy. A suitable formulation can be developed for either
slow release or no release of the enzyme.

5 Catalase in PBS is mixed with the prepolymer in the following formulation:

	Catalase at the desired amount	
	PEG DA (MW 10000)	35%
	PEG DA (MW 1000)	5%
10	PBS	60%

with 2,2-dimethoxy, 2-phenyl acetophenone at 1.6% of the above solution.

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15 This solution is placed in mineral oil at a ratio of 1 part catalase/prepolymer solution to 5 parts mineral oil and is rapidly agitated with a motorized mixer to form an emulsion. This emulsion is illuminated with a long-wavelength ultraviolet light (360nm) for 5 min to crosslink the PEG prepolymer to form a gel. The mw of the prepolymer may be selected to resist the diffusion of the catalase from the gel, with smaller PEG DA

20 molecular weights giving less diffusion.

PEG DA of MW 10,000, further crosslinked with PEG DA 1000, should possess the appropriate permselectivity to restrict catalase diffusion, and it should possess the appropriate permselectivity to permit the diffusion of hydrogen peroxide into

25 the gel-entrapped catalase to allow the enzymatic removal of the hydrogen peroxide from the bloodstream. Furthermore, it should possess the appropriate biocompatibility to circulate within the bloodstream.

5 In this way, the gel is used for the controlled
containment of a bioactive agent within the body. The active
agent (enzyme) is large and is retained within the gel, and the
agent upon which it acts (substrate) is small and can diffuse
into the enzyme rich compartment. However, the active agent is
10 prohibited from leaving the body or targeted body compartment
because it cannot diffuse out of the gel compartment.

Example 26

Use of PEO Gels as Adhesive to

Rejoin Severed Nerve

15 A formulation of PEG tetraacrylate (10%, 18.5K), was
used as adhesive for stabilizing the sutureless apposition of the
ends of transected sciatic nerves in the rat. Rats were under
pentobarbital anesthesia during sterile surgical procedures. The
sciatic nerve was exposed through a lateral approach by
20 deflecting the heads of the biceps femoralis at the mid-thigh
level. The sciatic nerve was mobilized for approximately 1 cm
and transected with iridectomy scissors approximately 3 mm
proximal to the tibial-peroneal bifurcation. The gap between the
ends of the severed nerves was 2-3 mm. The wound was irrigated
25 with saline and lightly swabbed to remove excess saline.
Sterile, unpolymerized PEG tetraacrylate solution was applied to
the wound. Using delicate forceps to hold the adventitia or
perineurium, the nerve ends were brought into apposition, the

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5 macromer solution containing 2,2-dimethoxy-2-phenoxyacetophenone
as a photoinitiator applied to the nerve ends and the wound was
exposed to long wavelength UV-light (365 nm) for about 10 sec to
polymerize the adhesive. The forceps were gently pulled away.
Care was taken to prevent the macromer solution from flowing
10 between the two nerve stumps. Alternatively, the nerve stump
junction was shielded from illumination, e.g., with a metal foil,
to prevent gelation of the macromer solution between the stumps;
the remaining macromer solution was then simply washed away.

In an alternative approach, both ends of the transected
15 nerve can be held together with one pair of forceps. Forceps
tips are coated lightly with petrolatum to prevent reaction with
the adhesive.

The polymerized adhesive serves to encapsulate the
wound and adhere the nerve to the underlying muscle. The
20 anastomosis of the nerve ends resists gentle mobilization of the
joint, demonstrating a moderate degree of stabilization. The
muscle and skin were closed with sutures. Re-examination after
one month shows that severed nerves remain reconnected, despite
unrestrained activity of the animals.

5

Example 27

Surgical Adhesive

Abdominal muscle flaps from female New Zealand white rabbits were excised and cut into strips 1 cm X 5 cm. The flaps were approximately 0.5 to 0.8 cm thick. The lap joint, 1 cm X 1 cm, was made using two such flaps. Two different PEO di- and tetra-acrylate macromer compositions, 0.4K (di-) and 18.5K (tetra-), were evaluated. The 0.4K composition was a viscous liquid and was used without further dilution. The 18.5K composition was used as a 23% w/w solution in HBS. 125 μ l of ethyl eosin solution in n-vinyl pyrrolidone (20 mg/ml) along with 50 μ l of triethanolamine was added to each ml of the adhesive solution. 100 μ l of adhesive solution was applied to each of the overlapping flaps. The lap joint was then irradiated by scanning with a 2 W argon ion laser for 30 seconds from each side. The strength of the resulting joints was evaluated by measuring the force required to shear the lap joint. One end of the lap joint was clamped and an increasing load was applied to the other end, while holding the joint horizontally until it failed. Four joints were tested for each composition. The 0.4K joints had a strength of 12.0 ± 6.9 KPa (mean \pm S.D.), while the 18.5K joints had a strength of 2.7 ± 0.5 KPa. It is significant to note that it was possible to achieve photopolymerization and reasonable joint strength despite the 6-8 mm thickness of tissue. A

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5 spectrophotometric estimate using 514 nm light showed less than
1% transmission through such muscle tissue.

Example 28

Modification of polyvinyl alcohol

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10 2 g of polyvinyl alcohol (mol wt 100,000-110,000) was
dissolved in 20 ml of hot DMSO. The solution was cooled to room
temperature and 0.2 ml of triethylamine and 0.2 ml of acryloyl
chloride was added with vigorous stirring, under an argon
atmosphere. The reaction mixture was heated to 70°C for 2 hr and
cooled. The polymer was precipitated in acetone, redissolved in
15 hot water and precipitated again in acetone. Finally it was
dried under vacuum for 12 hr at 60°C. 5-10% w/v solution of this
polymer in PBS was mixed with the UV photoinitiator and
polymerized using long wavelength UV light to make microspheres
200-1,000 microns in size.

20 These microspheres were stable to autoclaving in water,
which indicates that the gel is covalently cross-linked. The gel
is extremely elastic. This macromer, PVA multiacrylate, may be
used to increase the crosslinking density in PEG diacrylate gels,
with corresponding changes in mechanical and permeability
25 properties. This approach could be pursued with any number of
water-soluble polymers chemically modified with
photopolymerizable groups, for example with water-soluble
polymers chosen from polyvinylpyrrolidone, polyethyloxazoline,

5 polyethyleneoxide-polypropyleneoxide copolymers, polysaccharides
such as dextran, alginate, hyaluronic acid, chondroitin sulfate,
heparin, heparin sulfate, heparan sulfate, guar gum, gellan gum,
xanthan gum, carrageenan gum, and proteins, such as albumin,
collagen, and gelatin.

10

Example 29

Use of Alternative Photopolymerizable Moieties

Many photopolymerizable groups may be used to enable
gelation. To illustrate a typical alternative synthesis, a
synthesis for PEG 1K urethane methacrylate is described as
15 follows:

In a 250 ml round bottom flask, 10 g of PEG 1K diol was
dissolved in 150 ml benzene. 3.38 g of 2-
isocyanatoethylmethacrylate and 20 μ l of dibutyltin dilaurate were
slowly introduced into the flask. The reaction was refluxed for
20 6 hours, cooled and poured into 1000 ml hexane. The precipitate
was then filtered and dried under vacuum at 60°C for 24 hours.
In this case, a methacrylate free radical polymerizable group was
attached to the polymer via a urethane linkage, rather than an
ester link as is obtained, e.g. when reacting with aryloxyl
25 chloride.

5

Example 30

Formation of Alginate-PLL-alginate Microcapsules with
Photopolymerizable Polycations

Alginate-polylysine-alginate microcapsules are made by
adsorbing, or coacervating, a polycation, such as polylysine
10 (PLL), upon a gelled microsphere of alginate. The resulting
membrane is held together by charge-charge interactions and thus
has limited stability. To increase this stability, the
polycation can be made photopolymerizable by the addition of a
carbon-carbon double bond, for example. This can be used to
15 increase the stability of the membrane by itself, or to react,
for example, with photopolymerizable PEG to enhance
biocompatibility.

To illustrate the synthesis of such a
photopolymerizable polycation, 1 g of polyallylamine
20 hydrochloride was weighed in 100 ml glass beaker and dissolved in
10 ml distilled water (DW). The pH of the polymer solution was
adjusted to 7 using 0.2 M sodium hydroxide solution. The polymer
was then separated by precipitating in a large excess of acetone.
It was then redissolved in 10 ml DW and the solution was
25 transferred to 50 ml round bottom flask. 0.2 ml glycidyl
methacrylate was slowly introduced into the reaction flask and
the reaction mixture was stirred for 48 hours at room
temperature. The solution was poured into 200 ml acetone and the
precipitate was separated by filtration and dried in vacuum.

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5 This macromer is useful in photochemically stabilizing an
alginate-PLL-alginate, both in the presence or in the absence of
a second polymerizable species such as a PEG diacrylate.

In addition to use in encapsulating cells in materials
such as alginate, such photopolymerizable polycations may be
10 useful as a primer or coupling agent to increase polymer adhesion
to cells, cell aggregates, tissues and synthetic materials, by
virtue of adsorption of the photopolymerizable polymer bonding to
the PEG photopolymerizable gel.

Example 31

15 **Cellular Microencapsulation for Evaluation of**
Anti-Human Immunodeficiency Virus Drugs In Vivo

HIV infected or uninfected human T-lymphoblastoid cells
can be encapsulated into PEG gels as described for other cells
above. These microcapsules can be implanted in a nonhuman animal
20 and then treated with test drugs such as AZT or DDI. After
treatment, the microcapsules can be harvested and the
encapsulated cells screened for viability and functional normalcy
using a fluorescein diacetate/ethidium bromide live/dead assay.
Survival of infected cells indicates successful action of the
25 drug. Lack of biocompatibility is a documented problem in this
approach to drug evaluations, but the highly biocompatible gels
described herein solve this problem.

5

Example 32

Use of Alternative

Photoinitiator/Photosensitizer Systems

It is possible to initiate photopolymerization with a wide variety of dyes as initiators and a number of electron donors as effective cocatalysts. Table 10 illustrates photopolymerization initiated by several other dyes which have chromophores absorbing at widely different wavelengths. All gelations were carried out using a 23% w/w solution of 18.5 kD PEG tetraacrylate in HEPES buffered saline. These initiating systems compare favorably with conventional thermal initiating systems, as can also be seen from Table 10.

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Table 10

Polymerization Initiation

	INITIATOR	LIGHT SOURCE*	TEMPERATURE °C	APPROXIMATE GEL TIME, (SEC)
10	Eosin Y, 0.00015M, Triethanolamine 0.65M	S1 with UV filter	25	10
	Eosin Y, 000015M; Triethanolamine 0.65M	S4	25	0.1
15	Methylene Blue, 0.00024M; p- toluenesulfonic acid, 0.0048M	S3	25	120
	2,2-dimethoxy-2-phenyl acetophenone 900 ppm	S2	25	8
20	Potassium Persulfate 0.0168M	-	75	180
	Potassium Persulfate 0.0168M; tetramethyl ethylene-diamine 0. 039M	-	25	120
25	Tetramethyl ethylene- diamine 0.039M; Riboflavin 0.00047M	S1 with UV filter	25	300

* LIST OF LIGHT SOURCES USED

CODE	SOURCE
30	S1 Mercury lamp, LEITZ WETZLER Type 307-148.002, 100W
	S2 Black Ray longwave UV lamp, model B-100A W/FLOOD
	S3 MELLES GRIOT He-Ne laser, 10mW output, 1=632 nm
	S4 American laser corporation, argon ion laser, model 909BP-15-01001; 1=488 and 514 nm

35 Numerous other dyes can be used for

photopolymerization. These dyes include but are not limited to
Erythrosin, phloxime, rose bengal, thionine, camphorquinone,

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ethyl eosin, eosin, methylene blue, and riboflavin. Possible cocatalysts that can be used include but are not limited to: N-methyl diethanolamine, N,N-dimethyl benzylamine, triethanolamine, triethylamine, dibenzyl amine, N-benzyl ethanolamine, N-isopropyl benzylamine.

BIODEGRADABLE MACROMERS

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Table 11 shows the code names of the various macromers synthesized in or for use in the examples, along with their composition in terms of the molecular weight of the central PEG segment and the degree of polymerization of the degradable comonomer.

5 Table 11: Macromer Molecular Weight and Composition

	PEG molecular	Comonomer	D.P. of comonomer per OH group	Polymer weight Code
10	20,000	glycolide	15	20KG
	18,500	glycolide	2.5	18.5K
	10,000	glycolide	7	10KG
	6,000	glycolide	5	6KG
	4,000	glycolide	5	4KG
	1,000	glycolide	2	1KG
15	20,000	DL-lactide	10	20KL
	18,500	DL-lactide	10	18.5KL
	10,000	DL-lactide	5	10KL
	6,000	DL-lactide	5	6KL
	1,000	DL-lactide	2	1KL
	600	DL-lactide	2	0.6KL
20	600	DL-lactide + lactide 2;		0.6KLCL
		caprolactone (CL)	CL 1	
	18,500	caprolactone	2.5	18.5KCL
	18,500	-	-	18.5KCO

Example 33

Synthesis of Photopolymerized Biodegradable Hydrogels.

PEG-based hydrogels

PEG-based biodegradable hydrogels are formed by the rapid laser or UV photopolymerization of water soluble macromers.

30 Macromers, in turn, are synthesized by adding glycolic acid oligomers to the end groups of PEG and then capping with acrylic end groups. The PEG portions of the macromers confer water solubility properties, and subsequent polymerization results in cell-nonadhesive hydrogels. Glycolic acid oligomers serve as the

35 hydrolyzable fraction of the polymer network, while acrylic end

5 groups facilitate rapid polymerization and gelation of the
macromers.

In preparation for synthesis, glycolide (DuPont) or DL-
lactide (Aldrich) was freshly recrystallized from ethyl acetate.
PEG oligomers of various molecular weight (Fluka or Polysciences)
10 were dried under vacuum at 110°C prior to use. Acryloyl chloride
(Aldrich) was used as received. All other chemicals were of
reagent grade and used without further purification.

Macromer synthesis

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15 A 250 ml round bottom flask was flame dried under
repeated cycles of vacuum and dry argon. 20 gm of PEG (molecular
weight 10,000), 150 ml of xylene and 10 μ gm of stannous octoate
were charged into the flask. The flask was heated to 60°C under
argon to dissolve the PEG and cooled to room temperature. 1.16
gm of glycolide was added to the flask and the reaction mixture
20 was refluxed for 16 hr. The copolymer was separated on cooling
and was recovered by filtration. This copolymer was separated on
cooling and recovered by filtration. This copolymer (10K PEG-
glycolide) was used directly for subsequent reactions. Other
polymers were similarly synthesized using DL-lactide or ϵ -
25 caprolactone in place of glycolide and using PEG of different
molecular weights.

Synthesis of photosensitive oligomers (macromers):

19 gm of 10K PEG-glycolide copolymer was dissolved in
150 ml methylene chloride and refluxed with 1 ml acryloyl

5 chloride and 1.2 ml of triethylamine for 12 hr under an argon
atmosphere. The solid triethylamine hydrochloride was separated
by filtration and the polymer was precipitated by adding the
filtrate to a large excess of hexane. The polymer (capped by an
acrylate at both ends) was further purified by repeated
10 dissolution and precipitation in methylene chloride and hexane
respectively.

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Table 12 lists certain macromers synthesized. The
degree of polymerization of the glycolide chain extender was kept
low so that all polymers have approximately 10 ester groups per
chain, or about 5 per chain end. When these polymers are
15 photopolymerized, a crosslinked three-dimensional network is
obtained. However, each chain segment in the resulting network
needs just one ester bond cleaved at either end to "degrade."
These ester cleavages enable the chain to dissolve in the
20 surrounding physiological fluid and thereby be removed from the
implant site. The resulting hydrolysis products, PEG and
glycolic acid, are water soluble and have very low toxicity.

5 non-physiological pH which can kill or functionally impair cells.
Proteins are often exposed to conditions which are potentially
denaturing and can result in loss of biological activity.

Further, even if cells survive processing conditions,
the stringent requirements of encapsulating polymers for
10 biocompatibility, chemical stability, immunoprotection and
resistance to cellular overgrowth, restrict the applicability of
prior art methods. For example, the encapsulating method based
on ionic crosslinking of alginate (a polyanion) with polylysine
or polyornithine (polycation) (Goosen, M. F. A., et al. (1985)
15 Biotechnology and Bioengineering, 27:146) offers relatively mild
encapsulating conditions, but the long-term mechanical and
chemical stability of such ionically crosslinked polymers remains
doubtful. Moreover, these polymers when implanted in vivo, are
susceptible to cellular overgrowth (McMahon, J., et al. (1990) J.
20 Nat. Cancer Inst., 82(22) 1761-1765) which restricts the
permeability of the microcapsule to nutrients, metabolites, and
transport proteins from the surroundings. This has been seen to
possibly lead to starvation and death of encapsulated islets of
Langerhans cells (O'Shea, G. M. et al. (1986) Diabetes, 35:943-
25 946).

Thus, there is a need for a relatively mild cell
encapsulation method which offers control over properties of the
encapsulating polymer. The membranes must be non-toxically
produced in the presence of cells, with the qualities of being

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5 permselective, chemically stable, and very highly biocompatible.
A similar need exists for the encapsulation of biological
materials other than cells and tissues.

Biocompatibility

Materials are considered biocompatible if the material
10 elicits either a reduced specific humoral or cellular immune
response or does not elicit a nonspecific foreign body response
that prevents the material from performing the intended function,
and if the material is not toxic upon ingestion or implantation.
The material also must not elicit a specific reaction such as
15 thrombosis if in contact with the blood.

Use of Gels in Biomaterials

Gels made of polymers which swell in water such as poly
(HEMA), water-insoluble polyacrylates, and agarose, have been
shown to be capable of encapsulating islet cells and other animal
20 tissue (Iwata, H., et al. (1989) Diabetes, 38:224-225; Lambert,
F. V., et al. (1984) Appl. Biochem. Biotech, 10:101-105).
However, these gels have undesirable mechanical properties.
Agarose forms a weak gel, and the polyacrylates must be
precipitated from organic solvents, thus increasing the potential
25 for cytotoxicity. Dupuy et al. ((1988) J. Biomed. Mater. Res.,
22:1061-1070) have reported the microencapsulation of islets by
polymerization of acrylamide to form polyacrylamide gels.
However, the polymerization process, if allowed to proceed
rapidly to completion, generates local heat and requires the

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5 presence of toxic cross-linkers. This usually results in mechanically weak gels whose immunoprotective ability has not been established. Moreover, the presence of a low molecular weight monomer is required which itself is cytotoxic.

Microcapsules formed by the coacervation of alginate
10 and poly(L-lysine) have been shown to be immunoprotective e.g., O'Shea, G. M. et al. (1986) Diabetes, 35:943-946. However, implantation for periods up to a week has resulted in severe fibrous overgrowth on these microcapsules (McMahon, J., et al. (1990) J. Nat. Cancer Inst., 82(22) 1761-1765; O'Shea, G. M. et
15 al. (1986) Diabetes, 35:943-946).

Synthetic Biodegradable Polymers

The field of biodegradable polymers has developed rapidly since the synthesis and biodegradability of polylactic acid was first reported by Kulkarni et al., (1966) Arch. Surg.,
20 93:839. Several other polymers are known to biodegrade, including polyanhydrides and polyorthoesters, which take advantage of labile backbone linkages, as reported by Domb et al., 1989 Macromolecules, 22:3200; Heller et al., 1990 BIODEGRADABLE POLYMERS AS DRUG DELIVERY SYSTEMS, Chasin, M. and
25 Langer, R., Eds., Dekker, New York, 121-161. Since it is desirable to have polymers that degrade into naturally occurring materials, polyaminoacids have been synthesized, as reported by Miyake et al., (1974), for *in vivo* use. This was the basis for using polyesters (Holland et al., 1986 Controlled Release, 4:155-

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5 180) of α -hydroxy acids (viz., lactic acid, glycolic acid), which remain the most widely used biodegradable materials for applications ranging from closure devices (sutures and staples) to drug delivery systems (U.S. Patent No. 4,741,337 to Smith et al.; Spilizewski et al., (1985) J. Control. Rel. 2:197-203).

10 The time required for a polymer to degrade can be tailored by selecting appropriate monomers. Differences in crystallinity also alter degradation rates. Due to the relatively hydrophobic nature of these polymers, actual mass loss only begins when the oligomeric fragments are small enough to be
15 water soluble. Hence, initial polymer molecular weight influences the degradation rate.

Degradable polymers containing water-soluble polymer elements have been described. Sawhney et al., (1990) J. Biomed. Mater. Res. 24:1397-1411, copolymerized lactide, glycolide and ϵ -
20 caprolactone with PEG to increase its hydrophilicity and degradation rate. U.S. Patent No. 4,716,203 to Casey et al. (1987) synthesized a PGA-PEG-PGA block copolymer, with PEG content ranging from 5-25% by mass. U.S. Patent No. 4,716,203 to Casey et al. (1987) also reports synthesis of PGA-PEG diblock
25 copolymers, again with PEG ranging from 5-25%. U.S. Patent No. 4,526,938 to Churchill et al. (1985) described noncrosslinked materials with MW in excess of 5,000, based on similar compositions with PEG; although these materials are not water soluble. Cohn et al. (1988) J. Biomed. Mater. Res. 22:993-1009

5 described PLA-PEG copolymers that swell in water up to 60%; these polymers also are not soluble in water, and are not crosslinked. These materials all use both water-soluble polymers and degradable polymers, and they are all insoluble in water, collectively swelling up to about 60%.

10 Degradable materials of biological origin are well known, for example, crosslinked gelatin. Hyaluronic acid has been crosslinked and used as a degradable swelling polymer for biomedical applications (U.S. Patent No. 4,987,744 to Della Valle et al., U.S. Patent 4,957,744 to Della Valle et al. (1991) Polym. Mater. Sci. Eng., 62:731-735).

15 Use of Biodegradable Materials for Controlled Drug Release

Most hydrophilic drugs are mechanically dispersed as suspensions within solutions of biodegradable polymers in organic solvents. Protein and enzyme molecular conformations are frequently different under these circumstances than they would be in aqueous media. An enzyme dispersed in such a hydrophobic matrix is usually present in an inactive conformation until it is released into the surrounding aqueous environment subsequent to polymer degradation. Additionally, some proteins may be irreversibly denatured by contact with organic solvents used in dispersing the protein within the polymer.

25 Use of PEO in Biomaterials

The use of poly(ethylene oxide) (PEO) to increase biocompatibility is well documented in the literature. The

5 presence of grafted PEO on the surface of bovine serum albumin
has been shown by Abuchowski, A. et al. ((1977) J. Biol. Chem.,
252:3578) to reduce immunogenicity in a rabbit and to increase
circulation times of exogenous proteins in animals. The
biocompatibility of algin-poly(L-lysine) microcapsules has been
10 significantly enhanced by incorporating a graft copolymer of PLL
and PEO on the microcapsule surface (Sawhney, et al.,
Biomaterials 11:863-870 (1991)).

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The grafting of methoxy PEO onto polyacrylonitrile
surfaces was seen by Miyama et al. ((1988) J. Appl. Polym. Sci.,
15 35:115-125) to render the polyacrylonitrile surface relatively
non-thrombogenic. Nagoaka et al. (Polymers as Biomaterials,
Shalaby, S. W. ed., Plenum Press, New York) synthesized a graft
copolymer of methacrylates with PEO and found the resulting
polymer to be highly non-thrombogenic. Desai and Hubbell have
20 immobilized PEO on poly(ethylene terephthalate) surfaces by
forming a physical interpenetrating network (Desai et al., (1992)
Macromolecules 25:226); they have shown these surfaces to be
highly resistant to thrombosis (Desai et al, (1991) Biomaterials,
12:144) and to both mammalian and bacterial cell growth (Desai,
25 et al., submitted).

PEO is a unique polymer in terms of structure. The PEO
chain is highly water soluble and highly flexible. PEO chains
have an extremely high motility in water and are essentially non-
ionic in structure. The synthesis and characterization of PEO

5 derivatives which can be used for attachment of PEO to various
surfaces, proteins, drugs etc. has been reviewed (Harris, (1985)
JNS-Rev. Macromol. Chem. Phys., C25:325-373). Other polymers are
also water soluble and non-ionic, such as poly(N-vinyl
pyrrolidinone) and poly(ethyl oxazoline). These have been used
10 to reduce interaction of cells with tissues. Desai et al. (1991)
Biomaterials, 12:144. Water soluble ionic polymers, such as
hyaluronic acid, have also been used to reduce cell adhesion to
surfaces and can similarly be used.

Electron beam cross-linking has been used to synthesize
15 PEO hydrogels, and these biomaterials have been reported to be
non-thrombogenic (Sun, et al., (1987) Polymer Prepr., 28:292-294;
Dennison, H.A., (1986) Ph.D. Thesis. Massachusetts Institute of
Technology). However, use of an electron beam precludes the
presence of any living tissue due to the sterilizing effect of
20 this radiation. Also, the networks produced are difficult to
characterize due to the non-specific cross-linking induced by the
electron beam.

Photopolymerizable PEG diacrylates have been used to
entrap yeast cells for fermentation and chemical conversion
25 (Kimura et al. (1981) Eur. J. Appl. Microbio. Biotechnol., 11:78-
80; Omata et al., (1981) Eur. J. Appl. Microbial Biotechnol.,
11:199-204; Okada et al. (1987) Appl. Microbiol. Biotechnol.,
26:112-116). Other methods for encapsulation of cells within
materials photopolymerizable with short wavelength ultraviolet

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5 radiation have been used with microbial cells (Tanaka, et al.,
(1977) Eur. J. Biochem, 80:193-197; Omata, et al., (1979)
European J. Appl. Microbiol. Biotechnol., 6:207-215; Omata, et
al., (1979) Eur. J. Appl. Microbiol. Biotechnol. 8:143-155; Chun,
et al., (1981) J. Gen. App. Microbiol., 27:505-509; Fukui, et al.,
10 (1976) Febs Letters, 66:2; Fukui, et al., (1984) Advances in
Biochemical Engineering and Biotechnology, 29:1-33). However,
yeast cells and some microbial cells are much hardier and
resistant to adverse environments, elevated temperatures, and
short wavelength ultraviolet radiation than mammalian cells and
15 human tissues.

There are several problems with these methods,
including the use of methods and/or materials which are
thrombogenic or unstable *in vivo*, or require polymerization
conditions which tend to destroy living mammalian tissue or
20 biologically active molecules, for example, short wavelength
ultraviolet radiation. In order to encapsulate living tissue for
implantation in a human or other mammalian subject, the
polymerization conditions must not destroy the living tissue, and
the resulting polymer-coated cells must be biocompatible.

25 There is also a need to encapsulate materials within a
very thin layer of material that is permeable to nutrients and
gases, yet strong and non-immunogenic. For example, for
transplantation of islets of Langerhans, the islets, which have a
diameter of 100 to 200 microns, have in the past been

5 encapsulated within microspheres that have a diameter of 400 to
1000 microns. This large diameter can result in slowed diffusion
of nutritional molecules and large transplantation volumes.

10 In summary, there is a need for materials, and methods
of use thereof, which can be used to encapsulate cells and
tissues or biologically active molecules which are biocompatible,
do not elicit specific or non-specific immune responses, and
which can be polymerized in contact with living cells or tissue
without injuring or killing the cells, within a very short time
frame, and in a very thin layer. An important aspect of the use
15 of these materials *in vivo* is that they must be polymerizable
within the time of a short surgical procedure or before the
material to be encapsulated disperses, is damaged or dies.

20 It is therefore an object of the present invention to
provide a polymeric material that can be polymerized in contact
with living cells and tissues, and in a very short time period.

It is a further object of the present invention to
provide a polymeric material which is biocompatible and resistant
to degradation for a specific time period.

25 It is a still further object of the present invention
to provide a polymeric material which is permeable to nutrients
and gases yet can protect cells and tissues from *in vivo* attack
by other cells.

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5 It is yet a further object of the present invention to
provide implantable biodegradable materials and biodegradable
materials for encapsulation of cells and tissue.

 It is another object of the present invention to
provide biogels which can be both ionically and covalently
10 crosslinked.

 It is an additional object of the present invention to
provide a crosslinked biocompatible material which has at least
one ionically crosslinked component and at least one covalently
crosslinked component.

15 SUMMARY OF THE INVENTION

 This invention provides novel methods for the formation
of biocompatible membranes around biological materials using
photopolymerization of water soluble molecules. The membranes
can be used as a covering to encapsulate biological materials or
20 biomedical devices, as a "glue" to cause more than one biological
substance to adhere together, or as carriers for biologically
active species.

 Several methods for forming these membranes are
provided. Each of these methods utilizes a polymerization system
25 containing water-soluble macromers, species which are at once
polymers and macromolecules capable of further polymerization.
The macromers are polymerized using a photoinitiator (such as a
dye), optionally a cocatalyst, optionally an accelerator, and

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- 5 radiation in the form of visible or long wavelength UV light.
The reaction occurs either by suspension polymerization or by
interfacial polymerization. The polymer membrane can be formed
directly on the surface of the biological material, or it can be
formed on material which is already encapsulated.
- 10 The macromers, which are water soluble or substantially
water soluble, are too large to diffuse into the cells to be
coated. Examples of macromers include highly biocompatible PEG
hydrogels, which can be rapidly formed in the presence or absence
of oxygen, without use of toxic polymerization initiators, at
15 room or physiological temperatures, and at physiological pH.
- Some macromers of this invention include at least one
water soluble region, at least one region which is biodegradable,
usually by hydrolysis, and at least two free radical-
polymerizable regions. The regions can, in some embodiments, be
20 both water soluble and biodegradable.
- Ultrathin membranes can be formed by the methods
described herein. These ultrathin membranes allow for optimal
diffusion of nutrient and bioregulator molecules across the
membrane, and great flexibility in the shape of the membrane.
- 25 Such thin membranes produce encapsulated material with optimal
economy of volume. Biological material thus coated can be packed
into a relatively small space without interference from bulky
membranes.

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5 The thickness and pore size of membranes formed can be varied. This variability allows for "perm-selectivity" -- membranes can be adjusted to the desired degree of porosity, allowing only preferred molecules to permeate the membrane, while acting as a barrier against larger undesired molecules. Thus, 10 the membranes are immunoprotective in that they prevent the transfer of antibodies or cells of the immune system.

 When the encapsulated biological material is cellular in nature, the absence of small monomers in the polymerization solution prevents the diffusion of toxic molecules into the cell. 15 In this manner the present invention provides a polymerization system which is more biocompatible than any available in the prior art.

 Additionally, the polymerization method can utilize short bursts of visible or long wavelength UV light which is 20 nontoxic to biological material. Bioincompatible polymerization initiators employed in the prior art are also eliminated.

 According to the present invention, membrane formation occurs under physiological conditions. Thus, no damage is done to the enclosed biological material due to harsh pH, temperature, 25 or ionic conditions.

 Because the membrane adheres to the biological material, the membrane can be used as an adhesive to fasten more than one biological substance together. The macromers are polymerized in the presence of these substances which are in close proximity.

5 The membrane forms in the interstices, effectively gluing the substances together.

Additionally, utilizing the tendency of the membrane to adhere to biological material, a membrane can be formed around or on a biologically active substance to act as a carrier for that
10 substance.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 shows schematically illustrated macromers of the present invention where _____ is a water soluble core such as PEG; ~~~~~ is a hydrolyzably degradable extension such as a
15 polyglycolide; ===== is a polymerizable end cap or side chain such as an acrylate; and ----- is a water-soluble and hydrolyzable portion such as a hyaluronate.

Figure 2A is a schematic of dye-initiated polymerization of a PEG layer around crosslinked alginate microspheres.

20 Figure 2B is a photomicrograph of the alginate/poly(L-lysine) microspheres containing human islets of Langerhans coated with a PEG 18.5K tetraacrylate hydrogel using the dye binding method depicted in Figure 2A.

Figure 3 is a schematic of photopolymerization of a PEG
25 coating on alginate-poly(L-lysine) microspheres suspended in mineral oil.

5 Figure 4 is a photomicrograph of Islets of Langerhans isolated from a human pancreas encapsulated in a PEG 18.5K tetraacrylate hydrogel.

 Figure 5 is a schematic representation of coextrusion apparatus used for microencapsulation using laser polymerization

10 Figure 6 is a photomicrograph of microspheres produced by laser polymerization of PEG 400 diacrylate around cells.

 Figure 7A is a photomicrograph of alginate-PLL microspheres recovered after 4 days following implantation i.p. in mice.

 Figure 7B is a photomicrograph of Alginate-PLL microspheres
15 coated with a PEG 18.5K Da tetraacrylate, using the dye diffusion method depicted in Figure 1.

 Figures 8A-F is a graph of the number of cells versus gel composition, for the unattached cells obtained from lavage of the peritoneal cavity in mice with different PEO overcoat gel
20 compositions: a - 18.5k; b - 10% 0.5k, 90% 18.5k; c - 50% 18.5k, 50% 0.4k; d - 10% 0.4k, 90% 35k; e - 50% 0.4k, 50% 35k; and f - alginate-poly(L-lysine) control.

 Figure 9 is a graph of the % protein released versus time in minutes, for diffusion of bovine serum albumin (open squares),
25 human IgG (triangles) and human fibrinogen (closed squares) through a PEO 18.5K-tetraacrylate gel.

 Figure 10 is a graph of the % diffusion of bovine serum albumin over time in minutes through PEO 400 diacrylate (open squares) and PEG 18.5K-tetracrylate (triangles) gels.

5 Figure 11A is a graph of the length in mm of gel produced by
argon ion laser induced polymerization versus log (time) (ms) of
trimethylolpropane using an amine and ethyl eosin initiation
system.

10 Figure 11B is a photomicrograph of the spikes formed as a
result of laser irradiation of ethoxylated trimethylol propane
triacylate for durations of 67 ms, 125 ms, 250 ms, 500 ms, and 1
sec.

15 Figure 12A is a photomicrograph of human foreskin
fibroblasts cultured for 6 h on a glass coverslip coated with PEG
18.5K-tetraacylate gel.

Figure 12B is a photomicrograph of human foreskin
fibroblasts cultured for 6 h on a glass that was not coated with
PEG.

20 Figure 13 is a photomicrograph of PEG 18.5K-tetraacylate
microspherical gels, implanted in mice, and explanted after 4
days, showing very little fibrous overgrowth.

Figures 14A-C are creep curves for PEG diacylate and
tetraacylate gels; test and recovery loads are given below the
abscissa: A - 1k; B - 6K; and C - 18.5K PEG gels.

25 Figure 15 shows the degree of photopolymerization (dp)
calculated and found by NMR.

Figure 16A shows Human foreskin fibroblasts cultured for six
hours on glass coverslips coated with PEG 18.5K-glycolide
diacylate (18.5KG).

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5 Figure 16B shows Human foreskin fibroblasts cultured for six hours on glass coverslips not coated with PEG.

 Figure 17A shows the release of BSA from a PEG 1K (1000 molecular weight PEG) glycolide diacrylate with glycolide extensions (1 KG) hydrogel into PBS.

10 Figure 17B shows release of lysozyme from PEG 18.5K-DL-lactide tetraacrylate (18.5KL) into PBS.

 Figure 18A shows release of active recombinant tPA from a PEG 1K lactide diacrylate (1KL) hydrogel.

15 Figure 18B shows release of active recombinant t-PA from PEG 4K glycolide diacrylate (4KG) hydrogel.

 Figure 18C shows release of active recombinant tPA from a PEG 18.5K-glycolide diacrylate (18.5KG) hydrogel into PBS.

20 Figure 19A is a superior view of rabbit uterine horn used as a control. Distorted horn anatomy with 66% adhesions is evident. The horns are folded upon themselves.

 Figure 19B is a superior view of rabbit uterine horn treated with a photopolymerized biodegradable hydrogel, PEG 18.5KL. Horn anatomy is normal, with no adhesion bands visible.

25 Figure 20A is an environmental scanning electron micrograph (ESEM) of an untreated blood vessel following trauma.

 Figure 20B is an ESEM of a polymer coated blood vessel following trauma.

5

DETAILED DESCRIPTION

By a variety of methods, this invention provides a means for creating biocompatible membranes of varying thickness on the surface of a variety of biological materials. The polymerization occurs by a free-radical reaction, causing a "macromer" with at least two ethylenically unsaturated moieties to form a crosslinked polymer. The components of this reaction are:

- (1) a photoinitiator, preferably eosin dye;
- (2) a "macromer," preferably polyethylene glycol (PEG) diacrylate, m.w. 18.5 kD. This component is at once a polymer and a macromolecule capable of further polymerization;
- (3) optionally a cocatalyst, preferably triethanolamine; and
- (4) optionally, an accelerator.

These components are mixed in varying combinations, and the mixture is exposed to longwave UV or visible light ("radiation"), preferably of wavelength 350-700 nm, most preferred at 365-514 nm, to initiate polymerization. A network is formed as the macromers polymerize in a variety of directions.

5 POLYMERIZATION

Four methods are used to effect polymerization to form biocompatible membranes. These are referred to below as the "bulk suspension polymerization" method, the "microcapsule suspension polymerization" method, the "microcapsule interfacial polymerization" method, and the "direct interfacial polymerization" method. They utilize either suspension or interfacial polymerization techniques on either coated or uncoated biological material.

1. BULK SUSPENSION POLYMERIZATION METHOD

15 In this embodiment of the invention the core biological material is mixed in an aqueous macromer solution (composed of the macromer, cocatalyst and optionally an accelerator) with the photoinitiator. Small globular geometric structures such as spheres, ovoids, or oblongs are formed, preferably either by
20 coextrusion of the aqueous solution with air or with a non-miscible substance such as oil, preferably mineral oil, or by agitation of the aqueous phase in contact with a non-miscible phase such as an oil phase to form small droplets. The macromer in the globules is then polymerized when exposed to radiation.
25 Because the macromer and initiator are confined to the globules, the structure resulting from polymerization is a capsule in which the biological material is enclosed. This is a "suspension polymerization" whereby the entire aqueous portion of the globule

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5 polymerizes to form a thick membrane around the cellular material.

2. MICROCAPSULE SUSPENSION POLYMERIZATION METHOD

10 This embodiment of the invention employs microencapsulated material as a core about which the macromer is polymerized in a suspension polymerization reaction. The biological material is first encapsulated, such as in an alginate microcapsules. The microcapsule is then mixed as in the first embodiment with the macromer solution and the photoinitiator, and then polymerized by radiation. In the event an ionically crosslinkable material such as alginate is used for the first encapsulation, this results in a biocompatible material which is both ionically crosslinked and covalently crosslinked.

15 This method takes advantage of the extreme hydrophilicity of PEG macromer, and is especially suited for use with hydrogel microcapsules such as alginate-poly(L-lysine). The microsphere is swollen in water. When a macromer solution (with the initiating system) is forced to phase separate in a hydrophobic medium, such as mineral oil, the PEG macromer solution prefers to stay on the hydrophilic surface of the alginate microcapsule. When this suspension is irradiated, the PEG macromer undergoes polymerization and gelation, forming a thin layer of polymeric, water insoluble gel around the microsphere. Agarose beads have been used in an analogous way by Gin et al. (1987) J. Microencapsulation, 4:239-242 as scaffolds to

5 carry out polymerization of acrylamide. However, that method is limited by potential toxicity associated with the use of a low molecular weight monomer, as opposed to the macromeric precursors of the present invention.

10 This technique preferably involves coextrusion of the microcapsule in a solution of macromer and photoinitiator, the solution being in contact with air or a liquid which is non-miscible with water, to form droplets which fall to a container such as a petri dish containing a solution such as mineral oil in which the droplets are not miscible. The non-miscible liquid is
15 chosen for its ability to maintain droplet formation.

Additionally, if the membrane-encapsulated material is to be injected or implanted in an animal, any residue should be non-toxic and non-immunogenic. Mineral oil is a preferred non-miscible liquid.

20 On the petri dish the droplets are exposed to radiation which causes polymerization. This coextrusion technique results in a crosslinked polymer coat of greater than 50 microns thickness. Alternatively, the microcapsules may be suspended in a solution of macromer and photoinitiator which is agitated in
25 contact with a non-miscible phase such as an oil phase. The emulsion which results is irradiated to form a polymer coat, again of greater than 50 microns thickness.

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5 3. MICROCAPSULE INTERFACIAL POLYMERIZATION METHOD

 In this embodiment, the biological material is also
microencapsulated as in the previous method. However, rather
than suspension polymerization, interfacial polymerization is
utilized to form the membrane. This involves coating the
10 microcapsule with photoinitiator, suspending the microcapsule in
the macromer solution, and immediately irradiating. By this
technique a thin polymer coat, of less than 50 microns thickness,
is formed about the microcapsule, because the photoinitiator is
present only at the microcapsule surface and is given
15 insufficient time to diffuse far into the macromer solution. As
a result, the initiator is present in only a thin shell of the
aqueous solution, causing a thin layer to be polymerized.

 When the microcapsules are in contact with dye
solution, the dye penetrates into the inner core of the
20 microcapsule as well as adsorbing to the surface. When such a
microcapsule is put into a solution containing a macromer and,
optionally, a cocatalyst such as triethanolamine, and exposed to
laser light, initially all the essential components of the
reaction are present only at and just inside the interface of
25 microcapsule and macromer solution. Hence, the polymerization
and gelation (if multifunctional macromer is used) initially
takes place only at the interface, just beneath it, and just
beyond it. If left for longer periods of time, the dye starts

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5 diffusing from the inner core of the microsphere into the
solution; similarly, macromers start diffusing inside the core.

Polymerization and subsequent gelation are very rapid
(typical gelation times are 100 ms) (Fouassier, et al., (1985) J.
Polym. Sci., Polym. Chem. Ed., 23:569; Chesneau, et al., (1985)
10 Die Ange. Makromol. Chemie, 135:41, (1988) Makromol. Chem., Rapid
Commun., 9:223). Because diffusion is a much slower process than
polymerization, not the entire macromer solution is polymerized
or gelled. Essentially the reaction is restricted to the near
surface only. The dye, being a smaller molecule and being weakly
15 bound to the capsule materials, keeps diffusing out of the
microsphere. If this diffusion occurs under laser irradiation,
then dye at the interface is used continuously to form a thicker
gel layer. The thickness of the coating can thus be directed by
controlling the reaction conditions.

20 A schematic representation of this process is shown in
Figure 2A. The amount, thickness or size and rigidity of the gel
formed will depend on the size and intensity of the beam, time of
exposure, initiator, macromer molecular weight, and macromer
concentration (see below). Alginate/PLL microspheres containing
25 islets coated by this technique are shown in Figure 2B.

4. DIRECT INTERFACIAL POLYMERIZATION METHOD

The fourth embodiment of this invention utilizes
interfacial polymerization to form a membrane directly on the
surface of the biological material. This results in the smallest

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5 capsules and thus achieves optimal economy of volume. Tissue is
directly coated with photoinitiator, emersed in the macromer
solution, and immediately irradiated. This technique results in
a thin polymer coat surrounding the tissue since there is no
space taken up by a microcapsule, and the photoinitiator is again
10 present only in a thin shell of the macromer solution.

USE AS AN ADHESIVE

It is usually difficult to get good adhesion between
polymers of greatly different physicochemical properties. The
concept of a surface physical interpenetrating network was
15 presented by Desai and Hubbel (Desai et al. (1992) Macromolecules
25:226). This approach to incorporating into the surface of one
polymer a complete coating of a polymer of considerably different
properties involved swelling the surface of the polymer to be
modified (base polymer) in a mutual solvent, or a swelling
20 solvent, for the base polymer and for the polymer to be
incorporated (penetrant polymer). The penetrant polymer diffused
into the surface of the base polymer. This interface was
stabilized by rapidly precipitating or deswelling the surface by
placing the base polymer in a nonsolvent bath. This resulted in
25 entanglement of the penetrant polymer within the matrix of the
base polymer at its surface in a structure that was called a
surface physical interpenetrating network.

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5 This approach can be improved upon by photopolymerizing
the penetrant polymer upon the surface of the base polymer in the
swollen state. This results in much enhanced stability over that
of the previous approach and in the enhancement of biological
responses to these materials. The penetrant may be chemically
10 modified to be a prepolymer (macromer), i.e. capable of being
polymerized itself. This polymerization can be initiated
thermally or by exposure to visible, ultraviolet, infrared, gamma
ray, or electron beam irradiation, or to plasma conditions. In
the case of the relatively nonspecific gamma ray or electron beam
15 radiation reaction, chemical incorporation of particularly
reactive sites may not be necessary.

Polyethylene glycol (PEG) is a particularly useful
penetrant polymer for biomedical applications where the lack of
cell adhesion is desired. The previous work had demonstrated an
20 optimal performance at a molecular weight of 18,500 D without
chemical crosslinking. PEG prepolymers can be readily formed by
acrylation of the hydroxyl groups at its termini or elsewhere
within the chain. These prepolymers can be readily polymerized
by the above described radiation methods. Photoinitiated
25 polymerization of these prepolymers is particularly convenient
and rapid. There are a variety of visible light initiated and
ultraviolet light initiated reactions that are initiated by light
absorption by specific photochemically reactive dyes, described
elsewhere herein. This same approach can be used for biomedical

5 purposes with other water-soluble polymers, such as poly(N-vinyl pyrrolidinone), poly(N-isopropyl acrylamide), poly(ethyl oxazoline) and many others.

10 Additionally, it is usually difficult to obtain adhesives for wet surfaces and tissues. Water soluble prepolymers, for example PEG diacrylates, can be used for this purpose. When a water soluble polymer is placed in aqueous solution upon a tissue, the polymer diffuses into the surface of the tissue, within the protein and polysaccharide matrix upon the tissue but not within the cells themselves. When the water
15 soluble polymer is a prepolymer and a visible, ultraviolet or infrared photoinitiator is included, the polymer penetrant may be exposed to the appropriate light to gel the polymer. In this way, the polymer is crosslinked within and around the matrix of the tissue in what is called an interpenetrating network. If the
20 prepolymer is placed in contact with two tissues and the prepolymer is illuminated, then these two tissues are adhered together by the intermediate polymer gel.

BIOLOGICAL MATERIALS

25 Due to the biocompatibility of the materials and techniques involved, a wide variety of materials can be used in conjunction with the present invention. For encapsulation, the techniques can be used with mammalian tissue and/or cells, as well as sub-cellular organelles and other isolated sub-cellular

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5 components. The membranes can be crafted to meet the perm-
selectivity needs of the biological material enclosed. Cells
which are to be used to produce desired products such as proteins
are optimally encapsulated by this invention.

10 Examples of cells which can be encapsulated are primary
cultures as well as established cell lines, including transformed
cells. These include but are not limited to pancreatic islet
cells, human foreskin fibroblasts, Chinese hamster ovary cells,
beta cell insulomas, lymphoblastic leukemia cells, mouse 3T3
fibroblasts, dopamine secreting ventral mesencephalon cells,
15 neuroblastoid cells, adrenal medulla cells, and T-cells. As can
be seen from this partial list, cells of all types, including
dermal, neural, blood, organ, muscle, glandular, reproductive,
and immune system cells can be encapsulated successfully by this
method. Additionally, proteins (such as hemoglobin),
20 polysaccharides, oligonucleotides, enzymes (such as adenosine
deaminase), enzyme systems, bacteria, microbes, vitamins,
cofactors, blood clotting factors, drugs (such as TPA,
streptokinase or heparin), antigens for immunization, hormones,
and retroviruses for gene therapy can be encapsulated by these
25 techniques.

The biological material can be first enclosed in a
structure such as a polysaccharide gel. (Lim, U.S.P.N.
4,352,883; Lim, U.S.P.N. 4,391,909; Lim, U.S.P.N. 4,409,331;
Tsang, et al., U.S.P.N. 4,663,286; Goosen et al., U.S.P.N.

5 4,673,556; Goosen et al., U.S.P.N. 4,689,293; Goosen et al.,
U.S.P.N. 4,806,355; Rha et al., U.S.P.N. 4,744,933; Rha et al.,
U.S.P.N. 4,749,620, incorporated herein by reference.) Such gels
can provide additional structural protection to the material, as
well as a secondary level of perm-selectivity. If alginate is
10 used, it is preferred that the alginate be relatively high in α -
L-guluronic acid content. This "high G" content increases the
biocompatibility of the material. The alginate should be at
least 60% α -L-guluronic acid, and more preferably at least 70% α -
L-guluronic acid.

15 MACROMERS

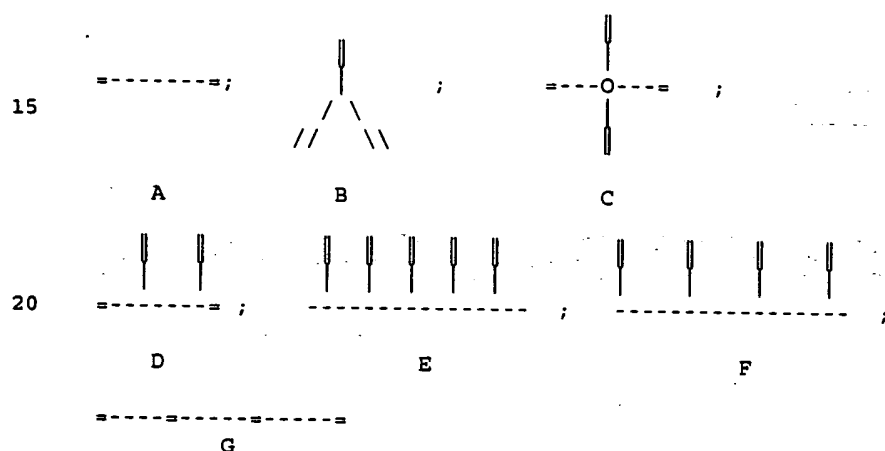
Polymerization via this invention utilizes macromers
rather than monomers as the building blocks. The macromers are
small polymers which are susceptible to polymerization into the
larger polymer membranes of this invention. Polymerization is
20 enabled because the macromers contain sites of unsaturation,
e.g., carbon-carbon double bond moieties, carbon-carbon triple
bond moieties, and the like, as well as sites of unsaturation
between carbon atoms and heteroatoms and between two heteroatoms.
Examples of carbon-carbon double bonds useful in this invention
25 include acrylate, methacrylate, ethacrylate, 2-phenyl acrylate,
2-chloro acrylate, 2-bromo acrylate, itaconate, acrylamide,
methacrylamide, and styrene groups. The macromers are water

5 soluble compounds and are non-toxic to biological material before and after polymerization.

A wide variety of substantially water soluble polymers exist, some of which are illustrated schematically below.

() represents a substantially water soluble region of the
10 polymer, and (=) represents a free radical polymerizable species.

Examples include:



Examples of A include PEG diacrylate, from a PEG diol;
25 of B include PEG triacrylate, formed from a PEG triol; of C include PEG-cyclodextrin tetraacrylate, formed by grafting PEG to a cyclodextrin central ring, and further acrylating; of D include PEG tetraacrylate, formed by grafting two PEG diols to a bis epoxide and further acrylating; of E include hyaluronic acid
30 methacrylate, formed by acrylating many sites on a hyaluronic acid chain; of F include PEG-hyaluronic acid-multiacrylate,

5 formed by grafting PEG to hyaluronic acid and further acrylating;
of G include PEG-unsaturated diacid ester formed by esterifying a
PEG diol with an unsaturated diacid.

Polysaccharides include, for example, alginate
(preferably high-G alginate), hyaluronic acid, chondroitin
10 sulfate, dextran, dextran sulfate, heparin, heparin sulfate,
heparan sulfate, chitosan, gellan gum, xanthan gum, guar gum, and
K-carrageenan. Proteins, for example, include gelatin, collagen,
elastin and albumin, whether produced from natural or recombinant
sources. In the event that a substance such as alginate or
15 hyaluronic acid is used, the resulting macromers will be both
ionically crosslinkable and covalently crosslinkable.

Photopolymerizable substituents preferably include
acrylates, diacrylates, oligoacrylates, dimethacrylates, or
oligomethoacrylates, and other biologically acceptable
20 photopolymerizable groups.

Synthetic Polymeric Macromers

The water-soluble macromer may be derived from water-
soluble polymers including, but not limited to, poly(ethylene
oxide) (PEO), poly(ethylene glycol) (PEG), poly(vinyl alcohol)
25 (PVA), poly(vinylpyrrolidone) (PVP), poly(ethyloxazoline) (PEOX)
polyaminoacids, pseudopolyamino acids, and polyethyloxazoline, as
well as copolymers of these with each other or other water
soluble polymers or water insoluble polymers, provided that the
conjugate is water soluble. An example of a water soluble

5 conjugate is a block copolymer of polyethylene glycol and polypropylene oxide, commercially available as a Pluronic™ surfactant.

Polysaccharide Macromers

Polysaccharides such as alginate (preferably high-G
10 alginate), hyaluronic acid, chondroitin sulfate, dextran, dextran sulfate, heparin, heparin sulfate, heparan sulfate, chitosan, gellan gum, xanthan gum, guar gum, water soluble cellulose derivatives, and carrageenan, which are linked by reaction with hydroxyls or amines on the polysaccharides can also be used to
15 form the macromer solution. As noted above, in the event that alginate, hyaluronic acid, or other ionically gellable materials are used, the macromers are both ionically crosslinkable and covalently crosslinkable.

Protein Macromers

20 Proteins such as gelatin, collagen, elastin, zein, and albumin, whether produced from natural or recombinant sources, which are made free-radical polymerization by the addition of carbon-carbon double or triple bond-containing moieties, including acrylate, diacrylate, methacrylate, ethacrylate, 2-
25 phenyl acrylate, 2-chloro acrylate, 2-bromo acrylate, itaconate, oligoacrylate, dimethacrylate, oligomethacrylate, acrylamide, methacrylamide, styrene groups, and other biologically acceptable photopolymerizable groups, can also be used to form the macromer solution.

5 MACROMERS FOR BIODEGRADABLE GELS

 In general terms, the macromers for biodegradable gels
are polymers that are soluble in aqueous solutions, or nearly
aqueous solutions, such as water with added dimethylsulfoxide.
They have three components including a biodegradable region,
10 preferably hydrolyzable under *in vivo* conditions, a water soluble
region, and at least two polymerizable regions. Examples of
these structures are shown in Figure 1.

 Structure A in Figure 1 shows a macromer having a water
soluble region (____), a water soluble and degradable component
15 (-----) appended to one another. Each has a polymerizable end
cap (=====). Structure B shows a major water soluble component
or core region (____) extended at either end by a degradable or
hydrolyzable component (-----) and terminated by, at either end,
a polymerizable component (=====). Structure C shows a central
20 degradable or hydrolyzable component (-----) bound to a water
soluble component (____) capped at either end by a
polymerizable component (=====). Structure D shows a central
water soluble component (____) with numerous branches of
hydrolyzable components (-----), each hydrolyzable component
25 being capped with a polymerizable component (=====). Structure
E shows a central biodegradable, hydrolyzable component (-----)
with three water soluble branches (____), each water soluble
branch being capped by a polymerizable component (=====).
Structure F shows a long central water soluble and hydrolyzable

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5 component (-----), each end being capped by a polymerizable
component (=====). Structure G shows a central water soluble
and hydrolyzable component (-----) capped at both ends by a
hydrolyzable component (-----), each hydrolyzable component
being capped by a polymerizable component (=====). Structure H
10 shows a central water soluble and degradable or hydrolyzable
component (-----) with end caps or branches of a polymerizable
component (=====). Structure I shows a central water soluble
component (_____) in circular form with water soluble branches
extended by a hydrolyzable component (-----) capped by a
15 polymerizable component (=====). Lastly, Structure J in Figure
1 shows a circular water soluble core component (_____) with
degradable branches (-----), each being capped by a
polymerizable component (-----).

The various structures shown in Figure 1 are exemplary
20 only. Those skilled in the art will understand many other
possible combinations which could be utilized for the purposes of
the present invention.

Used herein is the term "at least substantially water
soluble." This is indicative that the solubility should be at
25 least about 1 g/100 ml of aqueous solution or in aqueous solution
containing small amounts of organic solvent, such as
dimethylsulfoxide. By the term "polymerizable" is meant that the
regions have the capacity to form additional covalent bonds
resulting in macromer interlinking, for example, carbon-carbon

5 double bonds of acrylate-type molecules. Such polymerization is characteristically initiated by free-radical formation, for example, resulting from photon absorption of certain dyes and chemical compounds to ultimately produce free-radicals.

10 In a preferred embodiment, a hydrogel begins with a biodegradable, polymerizable, macromer including a core, an extension on each end of the core, and an end cap on each extension. The core is a hydrophilic polymer or oligomer; each extension is a biodegradable polymer or oligomer; and each end cap is an oligomer, dimer or monomer capable of cross-linking the
15 macromers. In a particularly preferred embodiment, the core includes hydrophilic poly(ethylene glycol) oligomers of molecular weight between about 400 and 30,000 Da; each extension includes biodegradable poly (α -hydroxy acid) oligomers of molecular weight between about 200 and 1200 Da; and each end cap includes an
20 acrylate-type monomer or oligomer (i.e., containing carbon-carbon double bonds) of molecular weight between about 50 and 200 Da which are capable of cross-linking and polymerization between copolymers. More specifically, a preferred embodiment incorporates a core consisting of poly(ethylene glycol) oligomers
25 of molecular weight between about 8,000 and 10,000 Da; extensions consisting of poly(lactic acid) oligomers of molecular weight about 250 Da; and end caps consisting acrylate moieties of about 100 Da molecular weight.

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5 Those skilled in the art will recognize that oligomers
of the core, extensions and end caps may have uniform
compositions or may be combinations of relatively short chains or
individual species which confer specifically desired properties
on the final hydrogel while retaining the specified overall
10 characteristics of each section of the macromer. The lengths of
oligomers referred to herein may vary from two mers to many, the
term being used to distinguish subsections or components of the
macromer from the complete entity.

Water Soluble Regions

15 In preferred embodiments, the core water soluble region
can consist of poly(ethylene glycol), poly(ethylene oxide),
poly(vinyl alcohol), poly(vinylpyrrolidone),
poly(ethyloxazoline), poly(ethylene oxide)-co-
poly(propyleneoxide) block copolymers, polysaccharides or
20 carbohydrates such as hyaluronic acid, dextran, heparan sulfate,
chondroitin sulfate, heparin, or alginate (preferably high-G
alginate), proteins such as gelatin, collagen, albumin,
ovalbumin, or polyamino acids.

Biodegradable Regions

25 The biodegradable region is preferably hydrolyzable
under *in vivo* conditions. For example, hydrolyzable group may be
polymers and oligomers of glycolide, lactide, ϵ -caprolactone,
other hydroxy acids, and other biologically degradable polymers
that yield materials that are non-toxic or present as normal

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5 metabolites in the body. Preferred poly(α -hydroxy acid)s are poly(glycolic acid), poly(DL-lactic acid) and poly(L-lactic acid). Other useful materials include poly(amino acids), poly(anhydrides), poly(orthoesters), poly(phosphazines) and poly(phosphoesters). Polylactones such as poly(ϵ -caprolactone),
10 poly(ϵ -caprolactone), poly(δ -valerolactone) and poly(gamma-butyrolactone), for example, are also useful. The biodegradable regions may have a degree of polymerization ranging from one up to values that would yield a product that was not substantially water soluble. Thus, monomeric, dimeric, trimeric, oligomeric,
15 and polymeric regions may be used.

Biodegradable regions can be constructed from polymers or monomers using linkages susceptible to biodegradation, such as ester, peptide, anhydride, orthoester, phosphazine and phosphoester bonds.

20 Polymerizable Regions

The polymerizable regions are preferably polymerizable by photoinitiation by free radical generation, most preferably in the visible or long wavelength ultraviolet radiation. The preferred polymerizable regions are acrylates, diacrylates,
25 oligoacrylates, methacrylates, dimethacrylates, oligomethoacrylates, or other biologically acceptable photopolymerizable groups.

Other initiation chemistries may be used besides photoinitiation. These include, for example, water and amine

- 5 initiation schemes with isocyanate or isothiocyanate containing
macromers used as the polymerizable regions.

MACROMER SIZE

- These macromers can vary in molecular weight from 0.2-
100 kD, depending on the use. The degree of polymerization, and
10 the size of the starting macromers, directly affect the porosity
of the resulting membrane. Thus, the size of the macromers are
selected according to the permeability needs of the membrane.
For purposes of encapsulating cells and tissue in a manner which
prevents the passage of antibodies across the membrane but allows
15 passage of nutrients essential for cellular metabolism, the
preferred starting macromer size is in the range of 10 kD to 18.5
kD, with the most preferred being around 18.5 kD. Smaller
macromers result in polymer membranes of a higher density with
smaller pores.

20 PHOTOINITIATING DYES

- The photoinitiating dyes capture light energy and
initiate polymerization of the macromers. Any dye can be used
which absorbs light having frequency between 320 nm and 900 nm,
can form free radicals, is at least partially water soluble, and
25 is non-toxic to the biological material at the concentration used
for polymerization. Examples of suitable dyes are ethyl eosin,
eosin Y, fluorescein, 2,2-dimethoxy,2-phenylacetophenone, 2-

- 5 methoxy, 2-phenylacetophenone, camphorquinone, rose bengal, methylene blue, erythrosin, phloxime, thionine, riboflavin and methylene green. The preferred initiator dye is ethyl eosin due to its spectral properties in aqueous solution.

COCATALYST

- 10 The cocatalyst is a nitrogen based compound capable of stimulating the free radical reaction. Primary, secondary, tertiary or quaternary amines are suitable cocatalysts, as are any nitrogen atom containing electron-rich molecules. Cocatalysts include, but are not limited to, triethanolamine, triethylamine, ethanolamine, N-methyl diethanolamine, N,N-
15 dimethyl benzylamine, dibenzyl amine, N-benzyl ethanolamine, N-isopropyl benzylamine, tetramethyl ethylenediamine, potassium persulfate, tetramethyl ethylenediamine, lysine, ornithine, histidine and arginine.

20 RADIATION WAVELENGTH

- The radiation used to initiate the polymerization is either longwave UV or visible light, with a wavelength in the range of 320-900 nm. Preferably, light in the range of 350-700 nm, and even more preferred in the range of 365-514 nm, is used.
25 This light can be provided by any appropriate source able to generate the desired radiation, such as a mercury lamp, longwave UV lamp, He-Ne laser, or an argon ion laser.

5 THICKNESS AND CONFORMATION OF POLYMER LAYER

Membrane thickness affects a variety of parameters, including perm-selectivity, rigidity, and size of the membrane. In the interfacial polymerization method, the duration of the radiation can be varied to adjust the thickness of the polymer membrane formed. This correlation between membrane thickness and duration of irradiation occurs because the photoinitiator diffuses at a steady rate, with diffusion being a continuously occurring process. Thus, the longer the duration of irradiation, the more photoinitiator will initiate polymerization in the macromer mix, the more macromer will polymerize, and a thicker coat will be formed. Additional factors which affect membrane thickness are the number of reactive groups per macromer, the concentration of accelerators in the macromer solution. This technique allows the creation of very thin membranes because the photoinitiator is first present in a very thin layer at the surface of the biological material, and polymerization only occurs where the photoinitiator is present.

The suspension polymerization method forms a somewhat thicker membrane than the interfacial polymerization method. This is because polymerization occurs in the suspension method throughout the macromer mix. The thickness of membranes formed by the suspension method is determined in part by the viscosity of the macromer solution, the concentration of the macromer in that solution, the fluid mechanical environment of the suspension

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5 and surface active agents in the suspension. These membranes
vary in thickness from 50-300 microns. The shape of the
structure formed by suspension polymerization can be controlled
by shaping the reaction mix prior to polymerization. Spheres can
be formed by emulsion with a non-miscible liquid such as oil,
10 coextrusion with such a liquid, or coextrusion with air.
Cylinders may be formed by casting or extrusion, and slabs and
discoidal shapes can be formed by casting. Additionally, the
shape may be formed in relationship to an internal supporting
structure such as a screening network of stable polymers (e.g. an
15 alginate gel, preferably high-G alginate, or a woven polymer
fiber) or nontoxic metals.

The overall amount, thickness, and rigidity of the
membrane formed depends on the interaction of several parameters,
including the size and intensity of the radiation beam, duration
20 of exposure of the solution to the radiation, reactivity of the
initiator selected, macromer molecular weight, and macromer
concentration.

APPLICATIONS FOR THE MACROMERS

The invention can be used for a variety of purposes,
25 some of which are enumerated below, along with benefits which
accrue from the use of the invention. Some additional purposes
are illustrated by the Examples which follow.

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- 5 a. Microencapsulating cells: more biocompatible, stronger,
 more stable, better control of permselectivity, less
 toxic conditions
- b. Macroencapsulating cells: more biocompatible, stronger,
 more stable, better control of permselectivity, less
10 toxic conditions, easier to incorporate internal or
 external supporting structure
- c. Microencapsulating or macroencapsulating other tissues,
 with the same benefits
- d. Microencapsulating or macroencapsulating pharmaceuti-
15 cals: more biocompatible, less damaging to the
 pharmaceutical
- e. Coating devices: ease of application, more
 biocompatible
- f. Coating microcapsules: more biocompatible, strengthens
20 them, ease of coating
- g. Coating macrocapsules, microcapsules, microspheres and
 macrospheres: more biocompatible, ease of coating
- h. Coating tissues to alter adhesion of other tissues:
 ease of coating, less toxicity to the tissues,
25 conformal coating versus nonconformal
- i. Adhesive between two tissues: ease of adhesion,
 rapidity of forming adhesive bond, less toxicity to
 tissues

5 Applications for the Biodegradable Macromers

Further, the biodegradable macromers can be used for the following purposes.

Prevention of Surgical Adhesions

 A preferred application is a method of reducing
10 formation of adhesions after a surgical procedure in a patient.
The method includes coating damaged tissue surfaces in a patient
with an aqueous solution of a light-sensitive free-radical
polymerization initiator and a macromer solution as described
above. The coated tissue surfaces are exposed to light
15 sufficient to polymerize the macromer. The light-sensitive free-
radical polymerization initiator may be a single compound (e.g.,
2,2-dimethoxy-2-phenyl acetophenone) or a combination of a dye
and a cocatalyst (e.g., ethyl eosin and triethanol amine).

Controlled drug delivery

20 A second preferred application concerns a method of
locally applying a biologically active substance to tissue
surfaces of a patient. The method includes the steps of mixing a
biologically active substance with an aqueous solution including
a light-sensitive free-radical polymerization initiator and a
25 macromer as described above to form a coating mixture. Tissue
surfaces are coated with the coating mixture and exposed to light
sufficient to polymerize the macromer. The biologically active
substance can be any of a variety of materials, including
proteins, carbohydrates, nucleic acids, and inorganic and organic

5 biologically active molecules. Specific examples include
enzymes, antibiotics, antineoplastic agents, local anesthetics,
hormones, antiangiogenic agents, antibodies, neurotransmitters,
psychoactive drugs, drugs affecting reproductive organs, and
oligonucleotides such as antisense oligonucleotides.

10 In a variation of the method for controlled drug
delivery, the macromers are polymerized with the biologically
active materials to form microspheres or nanoparticles containing
the biologically active material. The macromer, photoinitiator,
and agent to be encapsulated are mixed in an aqueous mixture.
15 Particles of the mixture are formed using standard techniques,
for example, by mixing in oil to form an emulsion, forming
droplets in oil using a nozzle, or forming droplets in air using
a nozzle. The suspension or droplets are irradiated with a light
suitable for photopolymerization of the macromer.

20 Tissue Adhesives

Another use of the polymers is in a method for adhering
tissue surfaces in a patient. The macromer is mixed with a
photoinitiator or photoinitiator/cocatalyst mixture to form an
aqueous mixture and the mixture is applied to a tissue surface to
25 which tissue adhesion is desired. The tissue surface is
contacted with the tissue with which adhesion is desired, forming
a tissue junction. The tissue junction is then irradiated until
the macromers are polymerized.

5 Tissue Coatings

 In a particularly preferred application of these
macromers, an ultrathin coating is applied to the surface of a
tissue, most preferably the lumen of a tissue such as a blood
vessel. One use of such a coating is in the treatment or
10 prevention of restenosis, abrupt reclosure, or vasospasm after
vascular intervention. The photoinitiator is applied to the
surface of the tissue, allowed to react, adsorb or bond to
tissue, the unbound photoinitiator is removed by dilution or
rinsing, and the macromer solution is applied and polymerized.
15 As demonstrated below, this method is capable of creating uniform
polymeric coating of between one and 500 microns in thickness,
most preferably about twenty microns, which does not evoke
thrombosis or localized inflammation.

Tissue Supports

20 The macromers can also be used to create tissue
supports by forming shaped articles within the body to serve a
mechanical function. Such supports include, for example,
sealants for bleeding organs, sealants for bone defects and
space-fillers for vascular aneurisms. Further, such supports
25 include strictures to hold organs, vessels or tubes in a
particular position for a controlled period of time.

 The invention described herein is further exemplified
in the following Examples. While these Examples provide a

5 variety of combinations useful in performing the methods of the
invention, they are illustrative only and are not to be viewed as
limiting in any manner the scope of the invention.

Example 1

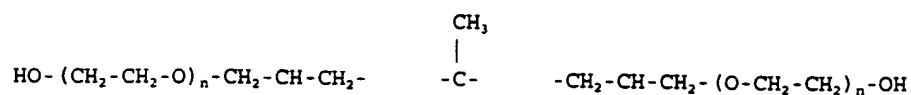
Synthesis of PEG 6 kD Diacrylate

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10 PEG acrylates of molecular weights 400 Da and 1,000 Da
were commercially available from Sartomer and Dajac Inc.
respectively. PEG 6 kD (20 g) was dissolved in 200 mL
dichloromethane in a 250 mL round bottom flask. The flask was
cooled to 0°C and 1.44 mL of triethyl amine and 1.3 mL of
15 acryloyl chloride were added with constant stirring under a dry
nitrogen atmosphere. The reaction mixture was then brought to
room temperature and stirred for 12 hr under a nitrogen
atmosphere. It was then filtered, and the filtrate was
precipitated by adding to a large excess of hexane. The crude
20 monomer was purified by dissolving in dichloromethane and
precipitating in hexane. Yield 69%.

Example 2

Synthesis of PEG 18.4 kD Tetraacrylate

A tetrafunctional water soluble PEG (30 g; m.w. 18.5
25 kD) having the following structure was purchased from
Polysciences, Inc.:



5 where $F_1 = \text{CONH}, \text{COO}$ or NHCOO

$X = \text{H}, \text{CH}_3, \text{C}_2\text{H}_5, \text{C}_6\text{H}_5, \text{Cl}, \text{Br}, \text{OH}$ or CH_2COOH

$F_2 = \text{COO}, \text{CONH}, \text{O}$ or C_6H_4 , AND

$R = \text{CH}_2$ or $-\text{alkyl}-$.

10 The PEG was dried by dissolving in benzene and
distilling off the water-benzene azeotrope. PEG 18.5 kD (59 g)
was dissolved in 300 mL of benzene in a 500 mL flask. To this,
3.6 mL of triethylamine and 2.2 mL of acryloyl chloride were
added under nitrogen atmosphere and the reaction mixture was
refluxed for 2 hours. It was then cooled and stirred overnight.
15 The triethyl amine hydrochloride was separated by filtration and
the copolymer was recovered from filtrate by precipitating in a
large excess of hexane. The polymer was further purified by
dissolving in methylene chloride and reprecipitating in hexane.
The polymer was dried at 50°C under vacuum for 1 day. Yield 68%.

20

Example 3

Coating of Islet-Containing Alginate-PLL

Microspheres by Surface Dye Adsorption

The microcapsule interfacial polymerization method was
used to form membrane around alginate-PLL microcapsules

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5 containing islets. Alginate-PLL coacervated microspheres,
containing one or two human pancreatic islets each, were
suspended in a 1.1% CaCl_2 solution and aspirated free of excess
solution to obtain a dense plug of microspheres. A solution of
ethyl eosin (0.04% w/v) was prepared in a 1.1 % CaCl_2 solution.
10 This solution was filter-sterilized by passage through a $0.45\mu\text{m}$
filter. The plug of microspheres was suspended in 10 mL of the
eosin solution for 2 min to allow uptake of the dye. The
microspheres were then washed four times with fresh 1.1% CaCl_2 to
remove excess dye. A solution of PEG 18.5 tetraacrylate (2 mL;
15 23% w/v) containing $100\mu\text{L}$ of a 3.5% w/v solution of
triethanolamine in HEPES buffered saline was added to 0.5 mL of
these microspheres. The microspheres were exposed to argon ion
laser light for 30 seconds with periodic agitation. The
suspension of microspheres was uniformly scanned with the light
20 during this period. The microspheres were then washed with
calcium solution and the process was repeated in order to further
stabilize the coating.

A static glucose stimulation test (SGS) was performed
on islets encapsulated in the microspheres coated with PEG gel.
25 Data for insulin secretion in response to this challenge appears
in Table 1. The islets were seen to be viable by dithizone
staining. The SGS test data confirm the vitality and
functionality of the islets.

5

TABLE 1

SGS

initial pulse subsequent

Glucose Concentration (mg%) 60 300 60

Insulin/Islet/hr (μ U/mL) *

10	Diffusion Overcoat Method	1.0	10.04 \pm 3.56	2.5450.76
	Mineral Oil Overcoat Method	1.0	10.23 \pm 3.28	1.0250.78
	Free Islet Control	1.0	3.74 \pm 1.4	1.950.17

* Values are mean \pm S.D., all are normalized as compared to the initial 60 mg %, after subjection to the 300 mg % glucose, the islets were resubjected to the initial dose.

15

PEG diacrylate macromers may be polymerized identically as the PEG tetraacrylate macromer described in this example.

Example 4

Coating Islet-Containing Alginate-PLL Microspheres

20 by the Microcapsule Suspension Polymerization Method

This method takes advantage of the hydrophilic nature of PEG monomers. Alginate/PLL microspheres (2 mL), containing one or two human pancreatic islets each, were mixed with PEG tetraacrylate macromer solution (PEG mol wt 18.5 kD, 23% solution in saline) in a 50 mL transparent centrifuge tube. Triethanolamine (0.1M) and 0.5 mM ethyl eosin were mixed with macromer solution. The excess of macromer solution was decanted,

25

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- 5 20 mL of mineral oil was added to the tube, and the reaction mixture was vortexed thoroughly for 5 minutes. Silicone oil will perform equally well in this synthesis but may have poorer adjuvant characteristics if there is any carry-over. Any other water-immiscible liquid may be used as the "oil" phase.
- 10 Acceptable triethanolamine concentrations range from about 1 mM to about 100mM. Acceptable ethyl eosin concentrations range from about 0.01 mM to more than 10 mM.

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15 The beads were slightly red due to the thin coating of macromer/dye solution, and they were irradiated for 20-50 sec with an argon ion laser (power 50-500 mW). Bleaching of the (red) ethyl eosin color suggested completion of the reaction. The beads were then separated from mineral oil and washed several times with saline solution. The entire procedure was carried out under sterile conditions.

- 20 A schematic representation of the microsphere coating process in oil is shown in Figure 3. Alginate/polylysine capsules are soluble in sodium citrate at pH 12. When these coated microspheres came in contact with sodium citrate at pH 12, the inner alginate/polylysine coacervate dissolves and a PEG
- 25 polymeric membrane could still be seen (crosslinked PEG gels are substantially insoluble in all solvents including water and sodium citrate at pH 12). The uncoated control microspheres dissolved completely and rapidly in the same solution.

5 A static glucose challenge was performed on the islets
as in Example 3. Data again appear in Table 1. The islets were
seen to be viable and functional.

Example 5

Encapsulation of Islets of Langerhans

10 This example makes use of the direct interfacial
polymerization. Islets of Langerhans isolated from a human
pancreas were encapsulated in PEG tetraacrylate macromer gels.
500 islets suspended in RPMI 1640 medium containing 10% fetal
bovine serum were pelleted by centrifuging at 100g for 3 min.
15 The pellet was resuspended in 1 mL of a 23% w/v solution of PEO
18.5 kD diacrylate macromer in HEPES buffered saline. An ethyl
eosin solution (5 μ L) in vinyl pyrrolidone (at a concentration of
0.5%) was added to this solution along with 100 μ L of a 5 M
solution of triethanolamine in saline. Mineral oil (20 mL) was
20 then added to the tube which was vigorously agitated to form a
dispersion of droplets 200-500 μ m in size. This dispersion was
then exposed to an argon ion laser with a power of 250 mW,
emitting at 514 nm, for 30 sec. The mineral oil was then
separated by allowing the microspheres to settle, and the
25 resulting microspheres were washed twice with PBS, once with
hexane and finally thrice with media.

Figure 4 shows islets of Langerhans encapsulated in a
PEO gel. The viability of the islets was verified by an acridine

5 orange and propidium iodide staining method and also by dithizone
staining. In order to test functional normalcy, an SGS test was
performed on these islets. The response of the encapsulated
islets was compared to that of free islets maintained in culture
for the same time period. All islets were maintained in culture
10 for a week before the SGS was performed. The results are
summarized in Table 2. It can be seen that the encapsulated
islets secreted significantly ($p < 0.05$) higher insulin than the
free islets. The PEO gel encapsulation process did not impair
function of the islets and in fact helped them maintain their
15 function in culture better than if they had not been
encapsulated.

TABLE 2

Islet Insulin secretion

Glucose Concentration (mg%)	60		
	60	300	60
	Insulin/Islet/hr ($\mu\text{U/mL}$) *		
Free islets	1.0	3.74 \pm 1.40	1.9 \pm 0.17
Encapsulated Islets	1.0	20.81 \pm 9.36	2.0 \pm 0.76

*Values are mean \pm S.D., normalized to initial basal level at
25 60 mg% glucose.

5

Example 6

Microencapsulation of Animal Cells

PEG diacrylates of different molecular weight were synthesized by a reaction of acryloyl chloride with PEG as in Example 1. A 20 to 30% solution of macromer was mixed with a cell suspension and the ethyl eosin and triethanolamine initiating system before exposing it to laser light through a coextrusion air flow apparatus, Figure 5. Microspheres were prepared by an air atomization process in which a stream of macromer was atomized by an annular stream of air. The air flow rate used was 1,600 cc/min and macromer flow-rate was 0.5 mL/min. The droplets were allowed to fall to a petri dish containing mineral oil and were exposed to laser light for about 0.15 sec each to cause polymerization and make them insoluble in water. Microspheres so formed were separated from the oil and thoroughly washed with PBS buffer to remove unreacted macromer and residual initiator. The size and shape of microspheres was dependent on extrusion rate (0.05 to 0.1 mL/min) and extruding capillary diameter (18 Ga to 25 Ga). The polymerization times were dependent on initiator concentration (ethyl eosin concentration (5 μ M to 0.5mM), vinyl pyrrolidone concentration (0.0% to 0.1 %), triethanolamine concentration (5 to 100 mM), laser power (10mW to 1W), and macromer concentration (>10% w/v).

A PEG diacrylate macromer of molecular weight 400 Da was used as a 30% solution in PBS, containing 0.1M

5 triethanolamine as a cocatalyst and 0.5mM ethyl eosin as a
photoinitiator. Spheres prepared using this method are shown in
Figure 6. The polymerizations were carried out at physiological
pH in the presence of air. This is significant since radical
polymerizations may be affected by the presence of oxygen, and
10 the acrylate polymerization is still rapid enough to proceed
effectively.

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The process also works at lower temperatures. For
cellular encapsulation, a 23% solution of PEO diacrylate was used
with initiating and polymerization conditions as used in the air
15 atomization technique. Cell viability subsequent to encapsula-
tion was checked by trypan blue exclusion assay. Human foreskin
fibroblasts (HFF), Chinese hamster ovary cells (CHO-K1), and a
beta cell insuloma line (RiN5F) were found to be viable (more
than 95%) after encapsulation. A wide range (> 10%) of PEG
20 diacrylate concentrations may be used equally effectively, as may
PEG tetraacrylate macromers.

Example 7

Coating of Animal Cell-Containing Alginate-PLL

Microspheres and Individual Cells by Surface Dye Adsorption

25 Alginate-PLL coacervated microspheres, containing
animal cells, were suspended in a 1.1% CaCl₂ solution and were
aspirated free of excess solution to obtain a dense plug of
microspheres. A solution was filter sterilized by passage

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5 through a 0.45 μ m filter. The plug of microspheres was suspended
in 10 mL of eosin solution for 2 min to allow dye uptake. A
solution of PEG 18.5 tetraacrylate (2 mL; 23% w/v) containing 100
 μ L of a 3.5 w/v solution of triethanolamine in HEPES buffered
saline was added to 0.5 mL of these microspheres. The
10 microspheres were exposed to an argon ion laser for 30 seconds
with periodic agitation. The suspension of microspheres was
uniformly scanned with the laser during this period. The
microspheres were then washed with calcium solution and the
process was repeated once more in order to attain a stable
15 coating.

In order to verify survival of cells after the overcoat
process, cells in suspension without the alginate/PLL micro-
capsule were exposed to similar polymerization conditions. 1 mL
of lymphoblastic leukemia cells (RAJI) (5×10^5 cells) was centri-
20 fugal at 300 g for 3 min. A 0.04% filter sterilized ethyl eosin
solution in phosphate buffered saline (PBS) (1 mL) was added and
the pellet was resuspended. The cells were exposed to the dye
for 1 min and washed twice with PBS and then pelleted.
Triethanolamine solution (10 μ L; 0.1M) was added to the pellet
25 and the tube was vortexed to resuspend the cells. 0.5 mL of PEO
18.5 kD tetraacrylate macromer was then mixed along with this
suspension and the resulting mixture was exposed to an argon ion
laser (514 nm, 50 mW) for 45 sec. The cells were then washed
twice with 10 mL saline and once with media (RPMI 1640 with 10%

5 FCS and 1% antibiotic, antimycotic). A thin membrane of PEO gel
may be observed forming around each individual cell.

No significant difference in viability was seen between
the control population (93% viable) and the treated cells (95%
viable) by trypan blue exclusion. An assay for cell viability
10 and function was performed by adapting the MTT-Formazan assay for
the RAJI cells. This assay indicates > 90% survival. Similar
assays were performed with two other model cell lines. Chinese
hamster ovary cells (CHO-K1) show no significant difference
($p < 0.05$) in metabolic function as evaluated by the MTT-Formazan
15 assay. 3T3 mouse fibroblasts also show no significant reduction
($p < 0.05$) in metabolic activity.

Example 8

Coating Animal Cell Containing Alginate-PLL

Microspheres by the Oil Suspension Method

20 Using the method described in Example 4, RAJI cells
contained in alginate-PLL microspheres were coated with a PEG
polymeric membrane. Viability of these cells was checked by
trypan blue exclusion and they were found to be more than 95%
viable.

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5

Example 9

Coating of Individual Islets of Langerhans by Surface Dye Adsorption

Using the method described in Example 7, ethyl eosin was adsorbed to the surfaces of islets, exposed to a solution of the PEG macromer with triethanolamine, and exposed to light from an argon-ion laser to form a thin PEG polymeric membrane on the surface of the islets. Islet viability was demonstrated by lack of staining with propidium iodide.

10

Example 10

15

Biocompatibility of PEO on Microspheres

In vivo evaluation of the extent of inflammatory response to microspheres prepared in Examples 7 and 8 was carried out by implantation in the peritoneal cavity of mice. Approximately 0.5 mL of microspheres were suspended in 5 mL of sterile HEPES buffered saline. A portion of this suspension (2.5 mL) was injected into the peritoneal cavity of ICR male Swiss white mice. The microspheres were recovered after 4 days by conducting a lavage of the peritoneal cavity with 5 mL of 10U heparin/mL PBS. The extent of cellular growth on the microspheres was visually inspected under a phase contrast microscope. The number of unattached cells present in the recovered lavage fluid was counted using a Coulter counter. Figure 7A shows a photograph of alginate-poly(L-lysine)

20

25

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5 microspheres explanted after 4 days, while Figure 7B shows
similar spheres which had been coated with PEG gel by the dye
diffusion process before implantation. As expected, bilayer
alginate-polylysine capsules not containing an outer alginate
layer to provide an extreme test of the ability of the PEG gel
10 layer to enhance the biocompatibility of the bilayer membrane,
were completely covered with cells due to the highly cell
adhesive nature of the PLL surface, whereas the PEG coated
microspheres were virtually free of adherent cells. Almost
complete coverage of alginate-poly(L-lysine) was expected because
15 polylysine has amino groups on the surface, and positively
charged surface amines can interact with cell surface
proteoglycans and support cell growth (Reuveny, et al., (1983)
Biotechnol. Bioeng., 25:469-480). The photographs in Figure 7B
strongly indicate that the highly charged and cell adhesive
20 surface of PLL is covered by a stable layer of PEG gel. The
integrity of the gel did not appear to be compromised.

 The non-cell-adhesive tendency of these microspheres
was evaluated as a percentage of the total microsphere area which
appears covered with cellular overgrowth. These results are
25 summarized in Table 3.

5

TABLE 3

Microsphere Coverage with Cell Overgrowth

	Composition of PEG gel	% Cell coverage
	18.5 kD	<1
	18.5 kD 90%:0.4 kD 10%	<1
10	18.5 kD 50%:0.4 kD 50%	<1
	35k 90%:0.4 kD 10%	5-7
	35k 50%: 0.4 kD 50%	<1
	Alginate poly(L-lysine)	60-80

15 An increase in cell count was a result of activation of resident macrophages which secrete chemical factors such as interleukins and induce nonresident macrophages to migrate to the implant site. The factors also attract fibroblasts responsible for collagen synthesis. The variation of cell counts with chemical composition of the overcoat is shown Figure 8 (A-F). It can be
20 seen from the figure that all PEG coated spheres have substantially reduced cell counts. This is consistent with the PEG overcoat generally causing no irritation of the peritoneal cavity.

25 However, PEG composition does make a difference in biocompatibility, and increasing molecular weights were associated with a reduction in cell counts. This could be due to the gels made from higher molecular weight oligomers having higher potential for steric repulsion due to the longer chain lengths.

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Example 11

Permeability of PEO Gels

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Bovine serum albumin, human IgG, or human fibrinogen (20 mg) was dissolved in 2 mL of a 23% w/v solution of oligomeric PEO 18.5 kD tetraacrylate in PBS. This solution was laser
10 polymerized to produce a gel 2cm X 2cm X 0.5 cm in size. The diffusion of bovine serum albumin, human IgG and human fibrinogen (mol wt 66 kD, 150 kD and 350 kD respectively) was monitored through the 2cm X 2cm face of these gels using a total protein assay reagent (Biorad). A typical release profile for a PEO 18.5
15 kD gel is shown in Figure 9. This gel allowed a slow transport of albumin but did not allow IgG and fibrinogen to diffuse. This indicates that these gels are capable of being used as immunoprotective barriers. This is a vital requirement for a successful animal tissue microencapsulation material.

20 The release profile was found to be a function of crosslink density and molecular weight of the polyethylene glycol segment of the monomer. Figure 10 shows the release of BSA through gels made from 23% solutions of PEO diacrylates and tetraacrylates of 0.4 kD and 18.5 kD, respectively. It is
25 evident that the 18.5 kD gel is freely permeable to albumin while the 0.4 kD gel restricted the diffusion of albumin. The release of any substance from these gels will depend on the crosslink density of the network and will also depend on the motility of

5 the PEG segments in the network. This effect is also dependent upon the functionality of the macromer. For example, the permeability of a PEG 18.5 kD tetraacrylate gel is less than that of an otherwise similar PEG 20 kD diacrylate gel.

10 In the case of short PEO chains between crosslinks, the "pore" produced in the network will have relatively rigid boundaries and will be relatively small and so a macromolecule attempting to diffuse through this gel will be predominantly restricted by a sieving effect. If the chain length between crosslinks is long, the chain can fold and move around with a high motility and, besides the sieving effect, a diffusing macromolecule will also encounter a free volume exclusion effect.

15 Due to these two contrasting effects a straightforward relation between molecular weight cutoff for diffusion and the molecular weight of the starting oligomer is not completely definable. Yet, a desired release profile for a particular protein or a drug such as a peptide may be accomplished by adjusting the crosslink density and length of PEG segments. Correspondingly, a desired protein permeability profile may be arranged to permit the diffusion of nutrients, oxygen, carbon dioxide, waste products, hormones, growth factors, transport proteins, and released cellularly synthesized proteins, while restricting the diffusion of antibodies and complement proteins and also the ingress of cells, to provide immunoprotectivity to transplanted cells or tissue. The three dimensional crosslinked

5 covalently bonded polymeric network is chemically stable for
long-term in vivo applications.

Example 12

Treatment of Silicone Rubber to Enhance Biocompatibility

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10 Pieces of medical grade silicone rubber (2 X 2 cm) were
soaked for 1 h in benzene containing 23% 0.4 kD PEG diacrylate
and 0.5% 2,2-dimethoxy-2-phenyl acetophenone. The thus swollen
rubber was irradiated for 15 min with a long wave UV lamp (365
nm). After irradiation, the sample was rinsed in benzene and
dried. The air contact angles of silicone rubber under water
15 were measured before and after treatment. The decreased contact
angle of 500 after treatment, over the initial contact angle of
630 for untreated silicone rubber reflects an increased
hydrophilicity due to the presence of the PEG gel on the rubber
surface.

20 This technique demonstrates that macromer
polymerization can be used to modify a polymer surface so as to
enhance biocompatibility. For instance, a polyurethane catheter
can be treated by this method to obtain an implantable device
coated with PEG. The PEG was firmly anchored to the surface of
25 the polyurethane catheter because the macromer was allowed to
penetrate the catheter surface (to a depth of 1-2 microns) during
the soaking period before photopolymerization. Upon irradiation,

5 an interpenetrating network of PEG and polyurethane results. The PEG was thereby inextricably intertwined with the polyurethane.

Example 13

Treatment of Polyurethane

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10 INTRACATH (Becton Dickinson) polyurethane intravenous catheters (19 ga) were modified at their outer surfaces with polyethylene glycol diacrylate (PEG DA) of molecular weight 400 and 10000. The prepolymer was dissolved in tetrahydrofuran (THF), a solvent for the polyurethane, at 50°C, where polyurethane dissolution is relatively slow. The following
15 solution was prepared and warmed to 50°C:

PEG DA (MW 400)	15%
PEG DA (MW 10000)	15%
THF	70%

with 2,2-dimethoxy, 2-phenyl actophenone at 1.6% of the above
20 solution.

2.5" length catheter segments were closed at one end by melting a 2 mm length by pressing with a hot metal spatula to from a flat tab. This tab was used to fix the catheter in the vessel wall in subsequent animal experiments. The catheter was
25 held with forceps at the tab end and dipped in the treatment solution for 1-3 sec, pulled out, and the excess fluid shaken off. The treated catheter was illuminated with an ultraviolet light (Black Ray, 360 nm) for 2-3 min, rotating the catheter. An

5 untreated control was similarly treated in 70% THF with 30% water replacing the PEG in the treatment solution.

Following this treatment, both the treated and control catheters were transferred to 100% methylene chloride to extract unreacted materials; this extraction was carried out for 36 hr
10 with solvent replacement every 6 hr. These catheters were then dried and transferred to 70% ethanol, and then into water before use.

A second composition was also investigated:

PEG DA (MW 400)	10%
15 PEG DA (MW 10000)	15%
Polyethylene oxide (MW 100,000)	5%
THF	70%

with 2,2-dimethoxy, 2-phenyl acetophenone at 1.6% of the above solution.

20 In this case, the polyethylene oxide of mw 100,000 was not a prepolymer and was immobilized within the PEG DA matrix by entanglement, rather than by chemical attachment.

Adult New Zealand male rabbits (7-10 lb) were anesthetized with rompun-acepromazien-ketamine. The animal was
25 shaved on the ventrolateral jugular and the vessel was raised. A catheter was inserted into the vessel with the tab outside, and tied in place via the tab with 4.0 nylon to the adventitia. The catheter was inserted 1.5 to 2.0" into the vessel. The skin incision was closed.

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5 After a period of 3 days, the animals were euthanized
by overdose of pentobarbital intraperitoneally. The vessel was
again raised and flushed with phosphate buffered saline (PBS) to
superficially rinse away blood between the catheter and the
vessel wall. Two 500 ml bottles, one filled with PBS and one
10 with formalin in PBS were hung from an i.v. pole scaffold, and
the hydraulic differential was used to perfusion fix the vessel.
The vessels were removed proximal and distal to the ends of the
catheters.

15 The treated catheters were completely wettable, and
were very slippery.

20 A total of 12 rabbits were catheterized for 72 hr. Six
were control, unmodified catheters. These catheters could not be
removed from the vessel wall without dissection, i.e. they were
tightly incorporated into the vessel. These catheters upon
removal were red, and the vessel was barely patent. By contrast,
the treated catheters were easily removable, the vessels were
clearly patent, and the catheters were not red. Under the light
microscope, a small amount of white thrombus could be seen on
both formulations of the catheter coating, with somewhat lesser
25 amounts on the formulation containing the polyethylene oxide
100,000.

5

Example 14

Treatment of Ultrafiltration Membranes

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The processes of Examples described above can be applied to the treatment of macrocapsular surfaces, such as those used for ultrafiltration, hemodialysis and non-microencapsulated immunoisolation of animal tissue. The macrocapsule in this case will usually be microporous with a molecular weight cutoff below 70,000 Da. It may be in the form of a hollow fiber, a spiral module, a flat sheet or other configuration. The surface of such a macrocapsule can easily be modified using the PEO gel coating process to produce a non-fouling, non-thrombogenic, and non-cell-adhesive surface. The coating serves to enhance biocompatibility and to offer additional immunoprotection. Materials which can be modified in this manner include polysulfones, cellulosic membranes, polycarbonates, polyamides, polyimides, polybenzimidazoles, nylons, and poly(acrylonitrile-co-vinyl chloride) copolymers and the like.

Depending on the physical and chemical nature of the surface a variety of methods can be employed to form biocompatible overcoats. Hydrophilic surfaces can simply be coated by applying a thin layer of a 30% w/v polymerizable solution of PEG diacrylate containing appropriate amounts of dye and amine. Hydrophobic surfaces can be first rendered hydrophilic by gas plasma discharge treatment and the resulting surface can then be similarly coated, or they may simply be

- 5 treated with a surfactant before or during treatment with the PEG diacrylate solution.

Example 15

Treatment of Textured Materials and Hydrogels

- The surface of materials having a certain degree of
- 10 surface texture, such as woven dacron, dacron velour, and expanded poly(tetrafluoroethylene) (ePTFE) membranes, was treated using the coating method described herein. Textured and macroporous surfaces allow greater adhesion of the PEG gel to the material surface. This allows the coating of relatively
- 15 hydrophobic materials such as PTFE and poly(ethylene terephthalate) (PET).

- Implantable materials such as enzymatic and ion sensitive electrodes, having a hydrogel (such as poly (HEMA), crosslinked poly(vinyl alcohol) and poly(vinyl pyrrolidone)) on
- 20 their surface, are coated with the more biocompatible PEO gel in a manner similar to the dye adsorption and polymerization technique used for the alginate-PLL microspheres.

Example 16

Treatment of Dense Materials

- 25 The surfaces of dense (e.g., nontextured, nongel) materials such as polymers (including PET, PTFE, polycarbonates, polyamides, polysulfones, polyurethanes, polyethylene,

5 polypropylene, polystyrene), glass, and ceramics can be treated
with PEO gel coatings. Hydrophobic surfaces were initially
treated by a gas plasma discharge to render the surface
hydrophilic. This ensures better adhesion of the PEO gel coating
to the surface. Alternatively, coupling agents may be used to
10 increase adhesion, as readily apparent to those skilled in the
art of polymer synthesis.

Example 17

Rate of Polymerization

To demonstrate rapidity of gelation in laser-initiated
15 polymerizations of multifunctional acrylic monomers, the kinetics
of a typical reaction were investigated. Trimethylolpropyl tri-
acrylate containing 5×10^{-4} M ethyl eosin as a photoinitiator in
10 μ moles of N-vinyl pyrrolidone per mL of macromer mix and 0.1M
of triethanolamine as a cocatalyst, was irradiated with a 500 mW
20 argon ion laser (514 nm wavelength, power 3.05×10^5 W/m², beam
diameter 1 mm, average gel diameter produced 1 mm). A plot of
the length of the spike of gel formed by penetration of the laser
beam into the gel versus laser irradiation time is shown in
Figure 11A. The spikes formed as a result of laser light
25 penetration into the macromer can be seen in Figure 11B.

A 23% w/w solution of various macromers in HEPES
buffered saline containing 3 μ L of initiator solution (300 mg/mL
of 2,2-dimethoxy-2-phenylacetophenone in N-vinyl pyrrolidone) was

5 used. 100 μ L of the solution was placed on a glass coverslip and irradiated with a low intensity long wave UV (LWUV) lamp (BlakRay, model 3-100A with flood). The times required for gelation to occur were noted and are given in Table 4. These times were typically in the range of 10 seconds.

10

TABLE 4

15

<u>Polymer Code</u>	<u>Gelling Time</u>	
	<u>Gel Time (sec)</u> (mean \pm S.D.)	
0.4 kD	6.9 \pm 0.5	
1 kD	21.3 \pm 2.4	
6 kD	14.2 \pm 0.5	
10 kD	8.3 \pm 0.2	
18.5 kD	6.9 \pm 0.1	
20 kD	9.0 \pm 0.4	

20

Time periods of about 10-100 ms were sufficient to gel a 300 μ m diameter droplet (a typical size of gel used in microencapsulation technology). This rapid gelation, if used in conjunction with proper choice of macromers, can lead to entrapment of living cells in a three dimensional covalently bonded polymeric network. The monochromatic laser light will not be absorbed by the cells unless a proper chromophore is present, and is considered to be harmless if wavelength is more than about 400 nm. Exposure to long wavelength ultraviolet light (>360 nm) is harmless at practical intensities and durations.

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Example 18

PEO Gel Interactions

Biocompatibility with HFF (human foreskin fibroblasts) cells was demonstrated as follows.

HFF cells were seeded on PEO 18.5 kD tetraacrylate gels at a density of 18,000 cells/cm² in Dulbecco's modification of Eagle's medium containing 10% fetal calf serum. The gels were then incubated at 37°C in a 5% CO₂ environment for 4 hr. At the end of this time the gels were washed with PBS to remove any non-adherent cells and were observed under a phase contrast microscope at a magnification of 200X. Figure 12A shows the growth of these cells on a typical PEG gel as compared to glass surface (Figure 12B). The number of attached cells/cm² was found to be 510 ± 170 on the gel surfaces as compared to 13,200 ± 3,910 for a control glass surface. The cells on these gels appeared rounded and were not in their normal spread morphology, strongly indicating that these gels do not encourage cell attachment.

Biocompatibility on microspheres was demonstrated as follows. Figure 13 shows a photograph of microspheres explanted from mice as in Example 10; after 4 days very little fibrous overgrowth was seen. The resistance of PEG chains to protein adsorption and hence cellular growth was well documented. Table 5 summarizes the extent of cellular overgrowth seen on these microspheres after 4 day intraperitoneal implants for various PEG diacrylate gels.

5

TABLE 5

PEG Diacrylate for Gels Extent of Cellular Overgrowth
(mol wt, Daltons)

	400	5-10%
10	1,000	15-25%
	5,000	3-5%
	6,000	2-15%
	10,000	10-20%
	18,500	4-10%
15		

Example 19

Characterization and Mechanical Analysis of PEO Gels

Solutions of PEO diacrylates (23% w/v; 0.4 kD, 6 kD, 10 kD) and PEG tetraacrylates (18.5 kD) were used. An initiator solution (10 μ L) containing 30 mg/mL of 2,2-dimethoxy-2-phenyl acetophenone in vinyl-2-pyrrolidone was used per mL of the macromer solution. The solution of initiator containing macromer was placed in a 4.0 X 1.0 X 0.5 cm mold and exposed to a long wave ultraviolet lamp (365 nm) for approximately 10 seconds to induce gelation. Samples were allowed to equilibrate in phosphate buffered saline (pH 7.4) for 1 week before analysis 1 performed.

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5 A series of "dogbone" samples (samples cut from a slab
into the shape of a dogbone, with wide regions at both ends and a
narrower long region in the middle) were cut for ultimate tensile
strength tests. Thickness of the samples was defined by the
thickness of the sample from which they were cut. These thick-
10 nesses ranged from approximately 0.5 mm to 1.75 mm. The samples
were 20 mm long and 2 mm wide at a narrow "neck" region. The
stress strain tests were run in length control at a rate of 4%
per second. After each test, the cross sectional area was
determined. Table 6 shows the ultimate tensile strength data.
15 It is seen that the lower molecular weight macromers in general
give stronger gels which were less extensible than those made
using the higher molecular weight macromers. The PEG 18.5 kD
tetraacrylate gel is seen to be anomalous in this series,
resulting from the multifunctionality of the macromer and the
20 corresponding higher crosslinking density in the resulting gel.
This type of strengthening result could be similarly achieved
with macromers obtained having other than four free radical
sensitive groups, such as acrylate groups.

5

TABLE 12

Polymer Code	<u>Macromers Synthesized</u>				Appearance
	Mol. Wt. Of	%	% ε-	Calculated	
	Central PEG	Glycolide	Caprolactone	Mol. Wt. Of	
	Chain	in	in Extremities	Extremities	
	(daltons)	Extremities		(daltons)	
0.4K	400	100	--	580	Viscous liquid
1KG	1000	100	--	300	Viscous liquid
4KG	4000	100	--	232	White solid
10KG	10000	100	--	580	White solid
18.5KG	18500	100	--	1160	Yellow solid
co18.5KGCL	18500	50	--	580	White solid

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Due to the presence of only a few units of glycolic acid per oligomeric chain, the solubility properties of the photocrosslinkable prepolymers are principally determined by the central PEG chain. Solubility of the macromers in water and methylene chloride, both of which are solvents for PEG, is not adversely affected as long as the central PEG segment has a molecular weight of 1,000 daltons or more. Solubility data for the prepolymers synthesized is given in Table 13.

5 Table 13: SOLUBILITY DATA

10

Solvent	1KG	4KG	10KG	18.5KG	TMP*
DMSO	-	■	-	■	■
Acetone	-	■	■	■	-
Methanol	-	■	-	■	-
Water	-	-	-	-	■
Hexane	■	■	■	■	■
Methylene Chloride	-	-	-	-	-
Cold Xylene	■	■	■	■	-
Hot Xylene	-	-	-	-	-
Benzene	■	■	■	■	-

15

- Soluble

■ Not Soluble

* Trimethylolpropane glycolide triacrylate

20 PEG chains with different degrees of polymerization of DL-lactide were synthesized to determine the degree of substitution for which water solubility of the macromers can be retained. The results are shown in Table 14. Beyond about 20% substitution of the hydrophilic PEG chain with hydrophobic DL-

25 lactoyl or acrylate terminals leads to the macromers becoming insoluble in water, though they are still soluble in organic solvents such as methylene chloride.

5 Table 14: Solubility of Macromers

D.P.* of			
D.P.* of	lactide	% extension of	Solubility
Ethylene Oxide or glycolide	PEG chain		in water
420	4	0.1	soluble
10 420	10	2.4	soluble
420	20	4.8	soluble
420	40	9.5	soluble
420	80	19	insoluble
23	2	8.7	soluble
15 23	4	17.4	soluble
23	10	43.5	insoluble
23	40	174	insoluble
5	4	80	insoluble
20 10	4	40	soluble

* degree of polymerization

Photopolymerization

The macromers can be gelled by photopolymerization using free radical initiators, with the presence of two acrylic double bonds per chain leading to rapid gelation. A 23% w/w solution of various degradable polymers in HEPES buffered saline containing 3 μ l of initiator solution (300 mg/ml of 2,2-dimethoxy-2-phenyl-acetophenone in n-vinyl pyrrolidone) was used. 100 μ l of the solution was placed on a glass coverslip and irradiated with a low intensity long wavelength UV (LWUV) lamp (Blak-Ray, model 3-100A with flood). The times required for gelation to occur were noted and are given below. These times are typically in the range of 10 seconds. This is very significant because these reactions are carried out in air (UV

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5 initiated photopolymerizations are slow in air as compared to an
inert atmosphere) and using a portable, low powered long wave UV
(LWUV) emitting source. Oxygen, which often inhibits free
radical reactions by forming species which inhibit propagation,
did not seem to slow down the polymerization. Such fast
10 polymerizations are particularly useful in applications requiring
in situ gelations. This rapid gelation is believed to be due to
the formation of micelle-like structures between the relatively
hydrophobic polymerizable groups on the macromer, thereby
increasing the local concentration of the polymerizable species
15 in aqueous solution and increasing polymerization rates.

Visible laser light is also useful for polymerization.
Low intensity and short exposure times make visible laser light
virtually harmless to living cells since the radiation is not
strongly absorbed in the absence of the proper chromophore.

20 Laser light can also be transported using fiber optics and can be
focused to a very small area. Such light can be used for rapid
polymerization in highly localized regions; gelation times for
selected prepolymers are given in Table 15. In each case, 0.2 ml
of a 23% w/v photosensitive oligomer solution is mixed with ethyl
25 eosin (10^{-4} M) and triethanol amine (0.01 to 0.1 M) and the
solution is irradiated with an argon ion laser (American argon
ion laser model 905 emitting at 514 nm) at a power of 0.2-0.5
W/cm². The beam is expanded to a diameter of 3 mm and the sample
is slowly scanned until gelation occurs.

5 Table 15: Gelation Times

	Polymer	UV polymerization *	Laser Polymerization**
		gelation time (mean ±S.D.) (s)	gelation time (s)
10	1KG	5.3±4.1	<1
	4KG	14.7±0.5	<1
	6KG	9.3±0.5	<1
	10KG	18.±0.8	<1
15	10KL	7.7±0.5	<1
	18KG	23.3±1.2	<1
	20KG	13.3±0.5	<1
20	* Initiator: 2,2-dimethoxy-2-phenylacetophenone, concentration 900 ppm: 0.2 ml of 23% monomer solution in PBS		
	** Argon ion laser emitting at 514nm. power 3 W/cm ² : ethyloeosin, triethanol amine initiating system: 0.2 ml of 23% monomer solution in PBS		

Biodegradability

Biodegradation of the resulting polymer network is an important criteria in many biomedical applications. Degradation of poly(glycolic acid and poly(DL-lactic acid) has been well documented in the literature. The degradation mainly takes place through the hydrolysis of the ester bond; the reaction is second order and highly pH dependent. The rate constant at pH 10 is 7 times faster than that at pH 7.2.

Such facile biodegradation is surprising because poly(α-hydroxyacidesters) are hydrophobic and highly insoluble in water. Accessibility of the polymer matrix to the aqueous

5 surrounding is therefore limited. However, because the networks
are hydrogels which are swollen with water, all the ester
linkages in the network are in constant contact with water with
the aqueous surroundings. This results in a uniform bulk
degradation rather than a surface degradation of these gels.

10 Table 16 gives hydrolysis data for some of these
networks; times listed are for complete dissolution of 60 mg of
gel at pH 7.2 and 9.6. As noted, most of the gels dissolve
within 12 hours at pH 9.6. 18.5k gel dissolves within 2.5 hr at
pH 9.6 whereas 18.5KCO gel does not dissolve in 3 days,
15 indicating that the lactoyl, glycoloyl, or ϵ -caprolactoyl ester
moiety is responsible for degradation of these networks. It also
can be seen that the 18.5KG gel hydrolyzes more rapidly than the
4KG gel. This may be due to the reduced hydrophilicity and
higher crosslink density of the latter gel.

20 **Table 16: Hydrolysis Data**

	Oligomer used for gelation	Time taken to dissolve gel at pH 9.6 (h)	Time taken to dissolve gel at pH 7.2 (days)
25	4KG	6.2	5.5
	10KG	12.25	5.5
	18.5KG	2.25	>7
	18.5KCL	>5 days	>7
	18.5KCO	>5 days	>7

5 Characterization of macromers

FTIR spectra of the prepolymers were recorded on a DIGILAB model FTS 15/90. The absorption at 1110 cm^{-1} (characteristic C-O-C absorption of PEG) shows the presence of PEG segments. The strong 1760 cm^{-1} absorption shows the presence of glycolic ester. The absence of hydroxyl group absorption around 3400 cm^{-1} and a weak acrylic double bond absorption at 1590 cm^{-1} shows the presence of acrylic double bonds at the end groups.

500 MHz proton and 125 MHz carbon-13 spectra were recorded on a GE 500 instrument. The presence of a very strong peak at 4.9 ppm due to CH_2 methylene from the PEG segment, a peak at 5.09 ppm due to the glycolic ester segment and an acrylic proton singlet at 5.8 ppm can be easily seen from proton NMR. The estimated molecular weight of PEG segment and glycolic acid segment for different copolymers is shown in Table 12. The carbonyl peak at 169.39 ppm from glycolic acid and 36.5 ppm peak from methylene carbons from PEG in carbon-13 NMR are consistent with the reported chemical composition of these copolymers.

Differential scanning calorimetry (Perkin Elmer DSC-7) was used to characterize the oligomers for thermal transitions. The oligomers were heated from -40°C to 200°C at a rate of $20^\circ\text{C}/\text{min}$, presumably causing polymerization. The polymer was then cooled to -40°C at a rate of $60^\circ\text{C}/\text{min}$ and again heated to 200°C at a rate of $20^\circ\text{C}/\text{min}$. The first scans of biodegradable

5 18.5K PEG glycolide tetraacrylate (18.5KG) oligomer were compared
to that of the non-degradable 18.5K PEG tetraacrylate (18.5KCO)
scan. It was seen that a glass transition appears in the 18.5KG
at -2°C while no such transition exists in the 18.5KCO. A small
melting peak at 140°C was also evident due to the few glycolic
10 acid mers which can crystallize to a limited extent. The melting
peak for PEG is shifted downwards in 18.5KG to 57°C from 60.7°C
for 18.5KCO. This is probably due to disturbance of the PEO
crystalline structure due to the presence of the glycolic acid
linkages. In the third cycle, by which time the oligomers have
15 presumably polymerized, the Tg and Tm transitions for the
glycolide segments can no longer be seen, indicating that a
crosslinked network has formed and the glycolic acid segments are
no longer capable of mobility.

20 The degree of polymerization (D.P.) of the degradable
segments added to the central water soluble PEG chain was
determined in several cases using ¹H NMR. The experimentally
determined D.P. was seen to be in good agreement with the
calculated number, as shown by Figure 15. Thus, the ring opening
reaction initiated by the PEG hydroxyls proceeds to completion,
25 giving quantitative yields.

Determination of Total Water, Free Water Bound Water

Solutions of various degradable macromers were made as
described above. Gels in the shape of discs were made using a
mold. 400 µl of solution was used for each disc. The solutions

5 were irradiated for 2 minutes to ensure thorough gelation. The disc shaped gels were removed and dried under vacuum at 60°C for 2 days. The discs were weighed (W1) and then extracted repeatedly with chloroform for 1 day. The discs were dried again and weighed (W2). The gel fraction was calculated as $W2/W1$.

10 This data appears in Table 17.

Subsequent to extraction, the discs were allowed to equilibrate with PBS for 6 hours and weighed (W3 after excess water had been carefully swabbed away). The total water content was calculated as $(W3-W2) \times 100/W3$. Differential scanning calorimetry (DSC) was used to determine the amount of free water that was available in the gels. A scan rate of 20°C/min was used and the heat capacity for the endotherm for water melting was measured (H1). The heat capacity of HBS was also measured (H2). The fraction of free water was calculated as $H1/H2$. The residual water was assumed to be bound due to hydrogen bonding with the PEO segments. The presence of free water in the gels was indicated. This free water can be expected to help proteins and enzymes entrapped in such gels in maintaining their native conformation and reducing deactivation. Thus these gels would appear to be suited for controlled release of biological micromolecules. The data for gel water content is summarized in Table 17.

5 Table 17: Hydrogel Water content

Polymer Code	% Free Water	% Bound Water	% Total Water	% Gel Content
1KG	68.4	14	82.3±2.6	61.3±5.2
4KG	78.0	9.3	87.3±1.8	56.3±0.9
10 6KG	74.8	13.4	88.1±3.3	66.5±2.35
10KG	83.7	10.8	94.5±0.5	54.3±0.6
10KL	82.0	9.7	91.7±0.5	63.9±3.7
18.5KG	71.8	22.3	94.0±0.4	47.0±4.9
20KG	79.8	14.8	94.5±0.4	44.5±4.8

15

Example 34

Use of multifunctional macromers.

30 g of a tetrafunctional water soluble PEG (MW 18,500) (PEG 18.5k) was dried by dissolving the polymer in benzene and distilling off the water benzene azeotrope. In a glove bag, 20 g of PEG 18.5 k, 1.881 g of glycolide and 15 mg of stannous octoate were charged into a 100 ml round bottom flask. The flask was capped with a vacuum stopcock, placed into a silicone oil bath and connected to a vacuum line. The temperature of the bath was raised to 200°C. The reaction was carried out for 4 hours at 200°C and 2 hours at 160°C. The reaction mixture was cooled, dissolved in dichloromethane and the copolymer was precipitated by pouring into an excess of dry ethyl ether. It was redissolved in 200 ml of dichloromethane in a 500 ml round bottom flask cooled to 0°C. To this flask, 0.854 g of triethylamine and 0.514 ml of acryloyl chloride were added under nitrogen atmosphere and the reaction mixture was stirred for 12 h. at 0°C. The triethyl

5 amine hydrochloride was separated by filtration and the copolymer
was recovered from filtrate by precipitating in diethyl ether.
The polymer was dried at 50°C under vacuum for 1 day.

Example 35

Synthesis of a photosensitive macromer containing DL-lactide

10 PEG (MW) 20,000) (PEG 20k) was dried by dissolving in
benzene and distilling off the water benzene azeotrope. In a
glove bag, 32.43 g of PEG 20k, 2.335 g of DL-lactide and 15 mg of
stannous octoate were charged into a 100 ml round bottom flask.
The flask was capped with a vacuum stopcock, placed into a
15 silicone oil bath and connected to a vacuum line. The
temperature of the bath was raised to 200°C. The reaction was
carried out for 4 hours at 200°C. The reaction mixture was
cooled, dissolved in dichloromethane and the copolymer was
precipitated by pouring into an excess of dry ethyl ether. It
20 was redissolved in 200 ml of dichloromethane in a 500 ml round
bottom flask cooled to 0°C. To this flask, 0.854 g of
triethylamine and 0.514 ml of acryloyl chloride were added under
nitrogen atmosphere and the reaction mixture was stirred for 12
hours at 0°C. The triethyl amine hydrochloride was separated by
25 filtration and the copolymer was recovered from filtrate by
precipitating in diethyl ether. The polymer was dried at 50°C
under vacuum for 1 day.

5

Example 36

Synthesis of a Photosensitive Precursor
Containing DL-Lactide and ϵ -Caprolactone.

PEG (MW 600) (PEG 0.6k) was dried by dissolving in benzene and distilling off the water benzene azeotrope. In a glove bag, 0.973 g of PEG 0.6k, 0.467 g of DL-lactide along with 0.185 g of ϵ -caprolactone and 15 mg of stannous octoate were charged into a 50 ml round bottom flask. The flask was capped with a vacuum stopcock, placed into a silicone oil bath and connected to a vacuum line. The temperature of the bath was raised to 200°C. The reaction was carried out for 4 hours at 200°C and 2 hours at 160°C. The reaction mixture was cooled, dissolved in dichloromethane and the copolymer was precipitated by pouring into an excess of dry ethyl ether. It was redissolved in 50 ml of dichloromethane in a 250 ml round bottom flask cooled to 0°C. To this flask, 0.854 g of triethylamine and 0.514 ml of acryloyl chloride were added under nitrogen atmosphere and the reaction mixture was stirred for 12 hours at 0°C. The triethylamine hydrochloride was separated by filtration and the copolymer was recovered from filtrate by precipitating in diethyl ether. The polymer was dried at 50°C under vacuum for 1 day and was a liquid at room temperature.

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5

Example 37

Selection of dyes for use in photopolymerization

It is possible to initiate photopolymerization with a wide variety of dyes as initiators and a number of electron donors as effective cocatalysts. Table 18 illustrates photopolymerization initiated by several other dyes which have chromophores absorbing at widely different wavelengths. All gelations were carried out using a 23% w/w solution of 18.5KG in HEPES buffered saline. These initiating systems compare favorably with conventional thermal initiating systems, as can also be seen from Table 18. Other photoinitiators that may be particularly useful are 2-methoxy-2-phenyl acetophenone and camphorquinone.

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5 Table 18: Polymerization Initiation of 18.5KG PEG

	INITIATOR	LIGHT SOURCE*	TEMPERATURE °C	GEL TIME (SEC)
10	Eosin Y, 0.00015M; Triethanolamine 0.65M	S1 with UV filter	25	10
	Eosin Y, 0.00015M; Triethanolamine 0.65M	S4	25	0.1
15	Methylene Blue, 0.00024M; p-toluenesulfonic acid, 0.0048M	S3	25	120
	2,2-dimethoxy-2-phenyl acetophenone 900 ppm	S2	25	8
	Potassium persulfate 0.0168M	-	75	180
20	Potassium Persulfate 0.0168M; tetramethyl ethylene-diamine 0.039M	-	25	120
25	Tetramethyl ethylene- diamine 0.039M; Riboflavin 0.00047M	S1 with UV filter	25	300

*LIST OF LIGHT SOURCES USED

	CODE	SOURCE	
30	S1	Mercury lamp, LEITZ WETSLER Type 307-148.002,	100W
	S2	Black Ray longwave UV lamp, model B-100A W/FLOOD	
	S3	MELLES GRIOT He-Ne laser, 10mW output, 1=632 nm	
	S4	American laser corporation, argon ion laser, model 909BP-15-01001; $\lambda=488$ and 514 nm	
35		Numerous other dyes can be used for	

photopolymerization. These dyes include but are not limited to:
 Erythrosin, phloxine, rose bengal, thionine, camphorquinone,
 ethyl eosin, eosin, methylene blue, and riboflavin. The several
 possible cocatalysts that can be used include but are not limited
 40 to: N-methyl diethanolamine, N,N-dimethyl benzylamine,

- 5 triethanol amine, triethylamine, dibenzyl amine, N-benzyl
ethanolamine, N-isopropyl benzylamine, and N-vinyl pyrrolidinone.

Example 38

Thermosensitive Biodegradable Gels from N-Isopropyl Acrylamide

Synthesis of low molecular weight polyisopropyl acrylamide

- 10 N-isopropyl acrylamide (NIPAAm) was recrystallized from
65:35 hexane benzene mixture. Azobisisobutyronitrile (AIBN) was
recrystallized from methanol. 1.5 g of NIPAAm was polymerized
using 3 mg of AIBN and 150 mg of mercaptoethanol in 1:1 acetone
water mixture (24 hours at 65°C). The viscous liquid after
15 polymerization was purified by dissolving in acetone and
precipitating in diethyl ether. Yield 80%.

- This hydroxy terminated low molecular weight
poly(NIPAAm) was used in chain extension reactions using
glycolide and subsequent endcapping reaction using acryloyl
20 chloride as described in other examples.

1 g of modified poly(NIPAAm) based oligomer and 0.2 g
1KL were dissolved in water at 0°C and polymerized at 0°C using
2-2-dimethoxy-2-phenylacetophenone (900 PPM).

5

Example 39

In Vitro Degradation

The gels were extracted as described in Example 32 to remove the unpolymerized macromer fraction and the gels were then placed in 50 mM HEPES buffered saline (0.9% NaCl), pH 7.4 at 37°C. Duplicate samples were periodically removed, washed with fresh HBS and dried at 100°C for 1 day and weighed to determine mass loss in the gel. The compositions of the various gels used were the same as described in the previous examples. Table 19 shows the extent of degradation of these gels given as percent of mass lost over time. The respective times are given in parenthesis along with the mass loss data.

Table 19: Gel Degradation

1KG	20.1% (1 d), 20.36±0.6 (2d), 21.7± (6d), 28.8±16.6 (10 d) estimated total Degradation time 45 days.
4KG	38.9 (1d), 60.3±4.2 (2d), 78.9 (3d), 99.3±4.7 (6d). Total degradation time 5.5 days.
6KG	18.3±6.8 (1d), 27.4±1.0 (2d), 32.8±11.3 (3d), 104.8±3.2 (5d). total degradation time 4.5 days 10KG 0.6±0.6 (8 hr), 100 (1d). Total degradation time 1 day.
10KL	10.0±4.84 (2d), 6.8±1.7 (3d), 4.5±3.1 (6d), 8.0±0.2 (10d). Total degradation time estimated to be 20 days.
20KG	68.1±4.2 (8hr), 99.7±0.3 (1d). Total degradation time 15 hr.

5

Example 40

Fibroblast adhesion and spreading

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15
20

The in vitro response of Human foreskin fibroblast (HFF) cells to photopolymerized gels was evaluated through cell culture on polymer networks. 0.2 ml of monomer solution was UV polymerized on an 18 x 18 mm glass coverslips under sterile conditions. HFF cells were seeded on these gels at a cell density of 1.8×10^4 cells/sq cm of coverslip area in Dulbecco's Modified Eagle's Medium (DMEM) supplemented with 10% fetal calf serum. The gels were incubated for 6 hr at 37°C in a 5% CO₂ environment, at the end of which they were washed twice with phosphate buffered saline (PBS). The adherent cells were fixed using a 2% glutaraldehyde solution in PBS. The gels were examined under a phase contrast microscope at a magnification of 200X, and the number of adherent and spread cells evaluated by examining five fields selected at predetermined locations on the coverslips.

The number of adherent cells is reported in Table 20 along with those for glass control surfaces. Cell adhesion is seen to be dramatically lowered on gel-coated glass.

5 **Table 20: Cell Adhesion**

	Surface	Attached Cells/cm ²
	glass	13220±3730
	18.5KG	250±240
	18.5KCL	1170±1020
10	18.5KCO	390±150

15 Typical photographs of these cells on the 18.5KCL gel surfaces and on control glass surfaces are shown in Figures 16A and 16B. It can be easily seen from Table 20 that these gels are highly resistant to cellular growth. Even the 18.5KCL is still less than 10% of the glass. Cells attached to the glass surface show a flattened and well-spread morphology whereas the few cells that are attached to the gel are rounded and loosely attached. This may result from the fact that hydrated PEG chains have a high motility and have been shown to be effective in minimizing protein adsorption. One of the mechanisms by which cell adhesion is mediated is through the interaction of cell surface receptors with adsorbed cell adhesion proteins. Thus the reduction in overall protein adsorption results in minimal cell adhesion protein adsorption and reduced cell adhesion.

25

Example 41

Release of Protein (Bovine Serum Albumin) from Polymers

1KG was used for this study. This macromer was liquid at room temperature and was used as such. 1 mg of bovine serum albumin (BSA) was added per ml of monomer solution along with 0.9

5 mg/ml of 2,2-dimethoxy-2-phenyl-acetophenone as initiator. The
protein was dissolved in the monomer solution and disc shaped
gels were made by exposing 0.2 g of macromer mixture to LWUV for
1 min. Two such discs were placed in a flask containing 20 ml of
PBS and incubated at 37°C. Two aliquots of 20 μ l each were
10 removed from these flasks periodically and the amount of BSA
released was assayed using the Bio-Rad total protein assay. The
release profile for BSA is shown in Figure 17A. It can be seen
that the release of BSA is relatively steady over more than a
month.

15 **Example 42**

Enzyme Release Assay

Water solubility of the macromers means gelation can be
carried out in a non-toxic environment. This makes these
materials suitable for intraoperative uses where *in situ* gelation
20 is needed. Since the precursors are water soluble, the gels can
be used as drug delivery vehicles for water soluble drugs,
especially macromolecular drugs such as enzymes, which would
otherwise be denatured and lose their activity. Release of
lysosome and tPA from the polymers was used to illustrate the
25 feasibility of using biodegradable hydrogels for controlled
release of biomolecules.

5 Lysozyme release

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The enzyme lysozyme (MW:14,400) is a convenient model for release of a low molecular weight protein from a biodegradable gel. The Biorad total protein assay was used to quantify the enzyme released. The enzyme was dissolved in PBS at a concentration of 20 mg/ml. The monomer PEG-dl-lactic acid-diacrylate was dissolved in PBS to produce a 40% solution. The lysozyme solution was added to the monomer solution to attain a 24% monomer solution. The monomer/lysozyme solution was polymerized under UV in a cylindrical mold, using 30 μ l of the initiator 2,2-dimethoxy-2-phenyl-acetophenone in 1-vinyl-2-pyrrolidone (30 mg/ml) as the initiator. The polymer was cut into 10 equal sized pieces and immersed in 10 ml PBS. Samples of the PBS were withdrawn at intervals and assayed for lysozyme released into the PBS. Lysozyme was released from the PEG-DL-lactic acid-diacrylate gel over an 8 day interval, with the maximum rate of release occurring within the first 2 days, as shown by Figure 17B.

20 Release of recombinant t-PA

Three macromers were used for these studies: 1KL, 4KG, and 18.5KG. The 1KL macromer was liquid at room temperature and was used as such. The second macromer, 4KG, was used as a 75% w/w solution in PBS. The third composition was a mixture of equal parts of 1KL and a 50% w/w solution of 18.5KG. 3.37 mg of tissue plasminogen activator (single chain, recombinant, M.W.

5 71,000) was added per gram of macromer solution along with 0.9
mg/ml of 2,2 dimethoxy 2 phenyl acetophenone as initiator. The
protein was dissolved with the macromer and disc shaped gels were
made by exposing 0.2 g of macromer mixture to LWUV for 1 minute.
Two such discs were rinsed with PBS, placed in a flask containing
10 5 ml of PBS and incubated at 37°C. Two aliquots of 100 µl each
were removed from these flasks periodically and the amount of
active t-PA released was assayed using a chromogenic substrate
assay (Kabi-vitrum). The release profiles from the 1K lactide
gels, 4K glycolide gels, and the 50/50 1K glycolide/18.5K
15 glycolide are shown in Figures 18A - 18C. Fully active tPA can
be released for periods up to at least two months.

By selecting an appropriate formulation, the release
rate can be tailored for a particular application. It is also
possible to combine formulations with different molecular weights
20 so as to synergistically achieve appropriate attributes in
release and mechanical characteristics.

For prevention of postoperative adhesions, in addition
to the barrier effect of the gels, the gels can be loaded with a
fibrinolytic agent to lyse incipient filmy adhesions which escape
25 the barrier effect. This further enhances the efficacy of
biodegradable gels in adhesion prevention.

5

Example 43

Toxicity of Polymers and Commercial Adhesives

To evaluate the toxicity of *in situ* polymerization of the macromer solutions described herein, as compared to commercial adhesives, 100 μ l of 18.5KCO prepolymer solution was placed on the right lobe of a rat liver and gelled by exposing it to LWUV for 15 sec; similarly, a few drops of a n-butyl cyanoacrylate based glue were placed on the left lobe. The liver was excised after a week, fixed in 10% neutral buffered formalin, blocked in paraffin, sectioned and stained using hematoxylin and eosin.

15

No adverse tissue reaction was evident on the surface of the lobe exposed to the biodegradable gel. No inflammatory reaction to the polymerization process can be seen. The epithelium looks normal, with no foreign body reaction.

20

In comparison, the lobe exposed to cyanoacrylate glue shows extensive tissue necrosis and scarring with 10-30 cell deep necrotic tissue. Fibrosis is evident in the necrotic portions close to underlying normal tissue.

Example 44

25

Prevention of Post-Surgical Adhesions with Photopolymerized Biodegradable Polymer

A viscous sterile 23% solution in phosphate buffered saline (8.0 g/l NaCl, 0.201 g/l KCl, 0.611 g/l Na_2HPO_4 , 0.191 g/l

5 KH_2PO_4 , pH 7.4) of polyethylene glycol (M.W. 18,500) which has
been chain extended on both ends with a short polyglycolide
repeat unit (average number of glycolidyl residues: 10 on each
end) and which has been subsequently terminated with an acrylate
group was prepared. Initiator needed for the crosslinking
10 reaction, 2,2-dimethoxy-2-phenyl acetophenone, was added to the
macromer solution to achieve an initiator concentration of 900
ppm. A 30 second exposure to a long wave UV lamp (Blak Ray) is
sufficient to cause polymerization.

Animal models evaluated

15 Animal models evaluated included a rat cecum model and
a rabbit uterine horn model. In the rat cecum model, 6 out of 7
animals treated with the macromer solution showed no adhesions
whatsoever, while untreated animals showed consistent dense
adhesion formation. In the rabbit uterine horn model, a
20 significant ($p < 0.01$) reduction in adhesion formation was seen in
the animals treated with the gel. Studies conducted in rats
using only the ungelled viscous precursor solution (no LWUV)
failed to prevent the formation of adhesions.

Rat cecum model

25 Twenty-one Sprague Dawley male rats having an average
weight of 250 gm were divided into three groups for treatment and
two for controls. The abdomen was shaved and prepared with a
betadine solution. A midline incision was made under Equithesin
anesthesia. The cecum was located and 4 to 5 scrapes were made

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5 on a region about 2 x 1 cm on one side of the cecum, using a 4 x
4 in gauze pad to produce serosal injury and punctate bleeding.
The abdominal incisions in these animals were closed using a
continuous 4-0 silk suture for the musculo-peritoneal layer and
7.5 mm stainless steel staples for the cutaneous layer. A
10 topical antibiotic was applied at the incision site.

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15 The first group consisted of 7 animals serving as
controls without treatment, to confirm the validity of the model.
The second group served as a control with the application of the
precursor but without photopolymerization to form the hydrogel.
After induction of the cecal injury, about 0.25 ml of the
precursor solution was applied to the injury site using a pipet.
The abdominal incision was then closed as above.

20 The third group served as the gel treatment group and
was prepared as the second group except that the precursor film
was exposed to a LWUV lamp for 45 seconds to cause gelation.
Both the obverse and reverse sides of the cecum were similarly
treated with precursor and light. No attempt was made to dry the
surface of the tissue, to remove blood, or to irrigate the area
prior to treatment.

25 The animals were sacrificed at the end of two weeks by
CO₂ asphyxiation. The incisions were reopened and adhesions were
scored for location, extent, and tenacity. The extent of
adhesions was reported as a percentage of the traumatized area of
the cecum which forms adhesions with adnexal organs or the

5 peritoneal wall. Tenacity of the adhesions was scored on a scale
from 0 to 4: no adhesions - grade 0; tentative transparent
adhesions which frequently separate on their own - grade 1;
adhesions that give some resistance but can be separated by hand
- grade 2; adhesions that require blunt instrument dissection to
10 separate - grade 3; and dense thick adhesions which require sharp
instrument dissection in the plane of the adhesion to separate -
grade 4.

Rat cecum model results

15 The control group without treatment shows consistently
dense and extensive adhesions. The extent of abraded area
covered with adhesions was seen to be $73 \pm 21\%$ (mean \pm S.D., $n=7$).
The severity of adhesions was grade 3.5 ± 0.4 . Most of the
adhesions were dense and fibrous, involving the cecum with
itself, with the peritoneal wall and with other organs such as
20 the liver, small intestine, and large intestine. Frequently the
mesentery was seen to be involved in adhesions. In the control
group with the application of precursor solution but without
gelation by exposure to the LWUV lamp, the extent of adhesion was
 $60 \pm 24\%$ ($n=7$), and the severity of adhesions was 3.1 ± 0.4 . In
25 the gel treated group, the cecum was seen to be completely free
of adhesions in 6 out of 7 animals. In one case, a grade 2
adhesion was seen with the mesentery over 10% of the area and a
grade 2.5 adhesion was seen over 15% of the area, bridging the
cecum to the sutures on the site of the incision in the

5 peritoneal wall. The overall adhesion extent for the group was
4%, and the overall severity was 0.32. No evidence of residual
gel was visible, the gel presumably having degraded within the
prior two weeks. The cecum appeared whitish with a fibrous layer
on the surface in the control group, but the tissue appeared
10 healthy and normal in animals treated with the gel.

Rabbit uterine horn model

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15 Eight sexually mature female New Zealand rabbits
between 2 and 3 kg in weight were prepared for surgery. A
midline incision was made in the lower abdominal region under
Rompun, Ketamine, and Acepromazine anesthesia. The uterine horns
were located and the vasculature to both horns was systematically
cauterized to induce an ischemic injury. One animal was rejected
from the study due to immature uterine horns. Seven rabbits were
selected for the treatment with only the photopolymerizable
20 hydrogel and two animals were selected for evaluating the
combined efficacy of the hydrogel with a fibrinolytic agent,
tissue plasminogen activator (tPA). 5 mg of tPA/ml macromer
solution was used in the latter case. After cauterization,
macromer solutions (0.5 ml) were applied along the horn and
25 allowed to coat the surface where the cauterization injury had
been induced. After uniform application of the solution was
complete, the horns were exposed to a LWUV lamp for 1 min to
induce gelation. The procedure was repeated on the reverse side
of the horns. The incisions were then closed using a continuous

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5 2-0 Vicryl (Ethicon) suture for the musculo-peritoneal layer and a
0 Vicryl (Ethicon) suture for the cutaneous layer. No
prophylactic antibiotics were administered. No postoperative
complications or infections were observed. Five animals were
used in the control group. The ischemic injury was made as
10 described and the incision was closed without the application of
the precursor; all techniques were identical between the
treatment group and the control group.

15 Controls were used where the same animal model was
subjected to surgery without application of the macromer; all
surgical techniques were identical between the treatment group
and the historical controls.

20 The rabbits were reoperated under Ketamine anesthesia
at the end of two weeks to evaluate adhesion formation; they were
sacrificed by intracardiac KCl injection. Adhesion formation was
evaluated for extent and tenacity. Extent of adhesion formation
was evaluated by measuring the length of the uterine horn that
formed adhesions with itself or with the peritoneal wall or other
organs. Tenacity of adhesion was classified as either filmy or
fibrous. Filmy adhesions were usually transparent, less strong,
25 and could be freed by hand. The fibrous adhesions were dense,
whitish, and usually required sharp instrument dissection to be
freed. In cases where only a single filmy adhesion band was
evident, a score of 5% was assigned.

5 Typical samples of the horn were excised for histology and were fixed in a 10% neutral buffered formalin solution. Paraffin sections of the samples were stained using hematoxylin and eosin.

Rabbit uterine horn model results

10 The adhesion score is the % of affected area occupied by the adhesions, with grading of each as being filmy or fibrous. Distorted horn anatomies were observed in control animals. The mean score in the control group was $50 \pm 15\%$ of the affected area of the horn being occupied by adhesions with 10% of these being
15 filmy and 90% fibrous. Distorted horn anatomies were observed, as can be seen from Figure 19A which presents a superior view of the uterine horn in an animal used as a control, which showed adhesions over 66% of the horn surface. The group of animals treated only with the photopolymerized macromer showed an
20 adhesion score of $13 \pm 11.4\%$ ($n=10$). Of these, 4 animals showed less than 5% adhesions with only an occasional filmy band visible.

 The animals treated with photopolymerized gel containing tPA showed further improved results over the "gel
25 only" animals. One animals showed a filmy band on both the right and left horn. They were assigned a score of 5% with a total score of 10%. The other animal did not show any adhesions at all. Thus the total score for these animals was $5 \pm 5\%$.

5 Figure 19B shows normal horn anatomy in a typical horn
which has undergone gel treatment. Adhesions are filmy in all
cases and no dense bands are seen. No traces of the remaining
gel could be observed. Typical samples of horns showing filmy
adhesions showed some fibrous tissue with a 6-15 cell thick layer
10 of fibroblasts showing some collagen fibrils but no formation of
dense collagen fibers. The horns showing no adhesions
occasionally showed a 1-4 cell thick layer of fibroblasts, but
mostly a normal epithelium with no evidence of inflammatory
cells.

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FOI b7D b7C b7E b7F b7G b7H b7I b7J b7K b7L b7M b7N b7O b7P b7Q b7R b7S b7T b7U b7V b7W b7X b7Y b7Z

15 This same procedure was slightly modified as described
below as a better mode of using the polymers to prevent
postoperative adhesions using the rat uterine horn model.

 Female rats were anesthetized with pentobarbital (50
mg/kg, intraperitoneally), and a midline laparotomy was
20 performed. The uterine horns were exposed, and the vasculature
in the arcade feeding the horns was systematically cauterized
using bipolar cautery; the most proximal and most distal large
vessel on each horn were not cauterized. Following this, the
antimesenteric surface of each horn was cauterized at two 1 mm
25 diameter spots on each horn, each separated by a 2 cm distance,
the pair centered along the length of each horn. Following
injury, 0.5 ml of macromer solution was applied per horn and was
gelled by exposure to long wavelength ultraviolet light (365 nm,
approximately 20 mW/cm²) for 15 sec per surface on the front side

5 and on the back side each. The uterus was replaced in the peritoneal cavity, and the musculo-peritoneal and skin layers were closed.

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10 The macromer consisted of a PEG chain of MW 8,000 daltons, extended on both sides with a lactic acid oligomer of an average degree of polymerization of 5 lactidyl groups, and further acrylated nominally at both ends by reaction with acryloyl chloride. In one batch, Batch A, the degree of acrylation was determined by NMR to be approximately 75%, and in another, Batch B, it was determined to be greater than approximately 95%. The macromer was dissolved in saline at a specified concentration, and the initiation system used was 2,2-dimethoxy-2-phenyl acetophenone from a stock solution in N-vinyl pyrrolidinone, the final concentration of 2,2-dimethoxy-2-phenyl acetophenone being 900 ppm and the final concentration of N-vinyl pyrrolidinone being 0.15%.

20 In one set of experiments, macromer from Batch A was applied in varying concentrations, and adhesions were scored at 7 days postoperatively. Scoring was performed by two means. The length of the horns involved in adhesions was measured with a ruler, and the fraction of the total length was calculated. The nature of the adhesions was also scored on a subjective scale, 0 being no adhesions, 1 being filmy adhesions that are easily separated by hand, and 2 being dense adhesions that can only be separated by sharp instrument dissection. Furthermore, one of

5 the samples contained tissue-plasminogen activator (t-PA), which
is known to reduce adhesions, at a concentration of 0.5 mg/ml
(0.5%) macromer solution. The results are shown in Table 21 for
macromer batch A and batch B.

10 In a third set of experiments, adhesions were formed in
female rats as described above, and the adhesions were surgically
lysed 7 days after the initial surgery. The extent and grade of
adhesions was scored during lysis. The animals were divided into
two groups, and one group was treated with macromer from Batch B
at a concentration of 10%. The results are shown in Table 21 as
15 batch B, 10%.

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5 Table 21: Reduction of Adhesions with Polymer.
Concentration Extent of Grade of Number of macromer
adhesions adhesions Animals
% (S.D.) (0-2)

<u>Polymer A</u>				
10 15%	24.6 (3.1)	1.1 (0.1)	7	
20%	33.6 (9.8)	1.2 (0.3)	7	
25%	37.5 (11.1)	1.2 (0.1)	7	
30%	54.2 (12.0)	1.6 (0.4)	6	
20% + t-PA	18.3 (6.4)	1.1 (0.1)	6	
15 Control (saline)	72.6 (18.7)	1.5 (0.2)	7	
<u>Polymer B</u>				
5%	22.1 (4.2)	1.2 (0.1)	7	
10%	10.0 (5.1)	1.0 (0)	7	
15%	17.8 (5.7)	1.0 (0)	7	
20%	26.3 (11.4)	1.4 (0.2)	7	
Control (saline)	75.9 (4.4)	1.8 (0.3)	7	
<u>Polymer B, 10%</u>				
Scoring performed at:	group that became:			
time of lysis	Controls	85.9 (9.7)	1.8 (0.1)	7
Time of lysis	Treatment	79.4 (6.8)	1.7 (0.2)	7
30 7 days post-lysis	Controls	78.8 (11.3)	1.8 (0.1)	7
7 days post-lysis	Treatment	28.2 (5.1)	1.0 (0)	7

35 The above results illustrate that the photopolymerized macromer can reduce or prevent post operative adhesions in both primary adhesions and adhesiolysis models, and moreover that the gel can be used to locally release a drug to exert a combined beneficial effect.

5

Example 45

Nerve anastomosis

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The sciatic nerve of a rat was aseptically severed using a scalpel and allowed to pull apart. The two ends of the nerve were reopposed using sterile forceps, and a 50% solution in
10 buffer of polymer 1KL, a macromer made from PEG 1K with lactide chain extension and acrylate termination, with 0.1% 2,2-dimethoxy-2-phenoxy acetophenone was applied to the nerve stumps. The affected area was illuminated with a 100 W LWUV lamp for 60 seconds, and an adhesive bond was observed to form between the
15 proximal and distal nerve stumps.

To ensure the biocompatibility of the applied material with the nerve tissue, the same solution of macromer was applied to nonsevered rat sciatic nerves, and the area of the incision was closed using standard small animal surgical technique. The
20 area was reopened at 1 hour or 24 hour postoperatively, and the affected area of the nerve was removed en block and prepared for transmission electron microscopy. No morphological differences were observable between the treated nerves at either time point as compared to control rat sciatic nerves that were otherwise
25 nonmanipulated, even though they had been traumatized and manipulated.

5

Example 46

Evaluation of PEG Based Degradable Gels as Tissue Adhesives

Abdominal muscle flaps from female New Zealand white rabbits were excised and cut into strips 1 cm X 5 cm. The flaps were approximately 0.5 to 0.8 cm thick. A lap joint, 1 cm X 1 cm, was made using two such flaps. Two different compositions, 0.6KL and 1 KL, were evaluated on these tissues. Both these compositions were viscous liquids and were used without further dilution. 125 μ l of ethyl eosin solution in N-vinyl pyrrolidone (20 mg/ml) along with 50 μ l of triethanolamine was added to each ml of the adhesive solution. 100 μ l of adhesive solution was applied to each of the overlapping flaps. The lap joint was then irradiated by scanning with a 2 W argon ion laser for 30 sec from each side. The strength of the resulting joints was evaluated by measuring the force required to shear the lap joint. One end of the lap joint was clamped and an increasing load was applied to the other end, while holding the joint was clamped and an increasing load was applied to the other end, while holding the joint horizontally until it failed. Four joints were tested for each composition. The 1KL joints had a strength of 6.6 ± 1.0 KPa (mean \pm S.D.), while the 0.6KL joints had a strength of 11.4 ± 2.9 KPa. It is significant to note that it was possible to achieve photopolymerization and reasonable joint strength despite the 6-8 mm thickness of tissue. A spectrophotometric estimate

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5 using 514 nm light showed less than 1% transmission through such muscle tissue.

Example 47

Coupling of Photopolymerizable Groups to Proteins (Albumin)

PEG (M.W. 2,000) monoacrylate (5g) was dissolved in 20
10 ml dichloromethane. Triethyl amine (0.523 g) and 2,2,2-trifluoroethanesulfonyl chloride (tresyl chloride) (0.017 g) were added and the reaction was allowed to proceed for 3 hours at 0°C under nitrogen atmosphere. The reaction mixture was then filtered and the dichloromethane evaporated to dryness. The
15 residue was redissolved in a small amount of dichloromethane and precipitated in diethyl ether. The polymer was then filtered and dried under vacuum for 10 hours and used directly in the subsequent reaction with albumin.

1 g of bovine serum albumin was dissolved in 200 ml of
20 sodium bicarbonate buffer at pH 9. Tresyl activated PEG monoacrylate (5 g) was added and the reaction was stirred for 24 hours at 25°C. Albumin was separated by pouring the reaction mixture into acetone. It was further purified by dialysis using a 15,000 daltons cutoff dialysis membrane. A 10% w/v solution of
25 the PEG acrylated albumin could be photopolymerized with long wave UV radiation using 0.9 mg/ml of 2,2 dimethoxy 2 phenylacetophenone as the initiator. In this gel the degradable segment is the protein albumin.

5

Example 48

Modification of Polysaccharides (Hyaluronic Acid)

In a dry 250 ml round bottom flask, 10 grams of PEG 400 monomethacrylate was dissolved in 100 ml dry dioxane, to which 4.053 g of carbonyl diimidazole (CDI) was slowly introduced under nitrogen atmosphere and the flask was heated to 50°C for 6 h. Thereafter the solvent was evaporated under vacuum and the CDI activated PEG monomer was purified by dissolving in dichloromethane and precipitating in ether twice.

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1 g of hyaluronic acid, 5 g of CDI activated PEG 400 monoacrylate were dissolved in 200 ml sodium borate buffer (pH 8.5) and the solution was stirred for 24 hours. It was then dialyzed using a 15,000 dalton cutoff dialysis membrane to remove unreacted PEG. A 10% w/v solution of the acrylated hyaluronic acid was photopolymerized with long wave UV radiation, using 0.9 mg/ml of 2,2-dimethoxy-2-phenylacetophenone as the initiator. In this gel, the degradable region is hyaluronic acid.

Example 49

PEG Chain Extended with Polyorthocarbonates and Capped

With Urethane Methacrylate

3, 9-bis(methylene) 2,4,8,10-tetraoxaspiro [5,5] undecane (1g) and polyethylene glycol (molecular weight, 1,000, 7.059 g) were weighed into a 250 ml Schlenk tube under dry nitrogen atmosphere in a glove bag. 50 ml of dry tetrahydrofuran

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5 was introduced under nitrogen atmosphere and reaction mixture was stirred for 6 hours at 50°C. This is a typical step growth reaction with a disturbed stoichiometry, resulting in low molecular weight polyoorthocarbonate with terminal hydroxy groups. The oligomer was separated by precipitating in hexane and dried under vacuum. 5 g of oligomer was redissolved in dry THF to which 20 μ l of dibutyltin dilaurate and 2 ml of 2-isocyanatoethyl methacrylate were slowly introduced and temperature was raised to 50°C. It was held there for 6 hours and cooled. The product was separated by precipitation in hexane. In this gel, the degradable region is a polyorthocarbonate.

Example 50

Microencapsulation of Animal Cells

A 23% w/w solution of 18.5KG in HEPES buffered saline (5 ml) was used to resuspend 10^6 CEM-SS cells. Ethyl eosin (10^{-4} M) was used as a solution in N-vinyl pyrrolidone as the initiator and triethanolamine (0.01 M) was used as the coinitiator. The solution was then exposed through a coextrusion apparatus to an argon ion laser (514 nm, 2 Watts). The coextrusion apparatus had mineral oil as the fluid flowing annularly (flow rate 4 ml/min) around an extruding stream of the precursor cell suspension (flow rate 0.5 ml/min). The microdriplets gelled rapidly on being exposed to the laser light and were collected in a container

5 containing PBS. The oil separated from the aqueous phase and the
microspheres could be collected in the PBS below. The
microspheres formed were thoroughly washed with PBS buffer to
remove unreacted monomer and residual initiator. The size and
shape of microspheres was dependent on extrusion rate and
10 extruding capillary diameter (18 Ga to 25 Ga). The
polymerization times were dependent on initiator concentration
(ethyl eosin 5 μ M to 0.5 mM, vinyl pyrrolidone (0.001% to 0.1%),
and triethanolamine (5 mM to 0.1 M), laser power (120 mW to 2W),
and monomer concentration (>10%w/v). Spheres prepared using this
15 method had a diameter from 500 μ m to 1,200 μ m. The
polymerizations were carried out at physiological pH in the
presence of air. This is significant since radical
polymerizations may be affected by the presence of oxygen. Cell
viability subsequent to encapsulation was checked by trypan blue
20 exclusion assay and the encapsulated cells were found to be more
than 95% viable after encapsulation.

Example 51

Various Formulations for the Prevention of

Post Operative Adhesions

25 The utility of PEG-oligo(α -hydroxy acid) diacrylates
and tetraacrylates to prevent postoperative adhesions was
evaluated in the rabbit uterine horn model as described above.
The following polymers were synthesized, as described above: PEG

5 6K lactide diacrylate (6KL), PEG 10K lactide diacrylate (10KL).
PEG 18.5K lactide (18.5KL), PEG 20K lactide (20KL). Solutions
with 24% polymer in PBS with 900 ppm 2,2-dimethoxy-2-phenyl
acetophenone, were prepared as described above. The solutions
were applied to the uterine horn after cautery of the vascular
10 arcade and illuminated with a 365 nm LWUV lamp, as described
above. In one formulation, 18.5KL, 5 mg t-PA was mixed into the
solution before application. Controls consisted of animals
manipulated and cauterized but not treated with macromer
solution. Measurement was performed on the 14th \pm 1 day. Extent
15 of adhesion was estimated from the fraction of the horn that was
involved in adhesions, and the tenacity of adhesions was scored
as 0, no adhesions; 1, filmy adhesions that offer no resistance
to dissection; 2, fibrous adhesions that are dissectable by hand;
3, fibrous adhesions that are dissectable by blunt instruments;
20 and 4, fibrous adhesions that are dissectable by sharp
instruments. The results were as follows, where the extent of
adhesions and the tenacity of the adhesions are shown.

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5 Table 22: Efficacy of Polymer in Preventing Adhesions.

Formulation	Number of animals	Extent, %, \pm	Tenacity, 0-4
		S.D.	\pm S.D.
6KL	7	0.9 \pm 1.7	0.9 \pm 0.7
10KL	7	0 \pm 0	0 \pm 0
20KL	6	4.4 \pm 5.0	0.9 \pm 0.7
18.5KL	7	8.9 \pm 13.1	1.6 \pm 1.3
t-PA Control	7	35 \pm 22	3.3 \pm 0.6

Example 52

15 Polymerization of Ultrathin Layers of Polymer on the Surface
of Blood Vessels to Reduce Thrombosis After Vessel Injury

Blood vessels were harvested from rats and were rinsed free of blood. The endothelium of the vessel were removed by inserting a wooden dowel and rotating the vessel over the dowel.

20 One vessel was used as a control, and was exposed to flowing blood as described below without further modification. Another vessel was treated first by exposure to eosin Y at 1 mM in saline, then rinsed in HEPES buffered saline, then filled with a solution of PEG-MA, PEG 10K with acrylate end-capped oligomers of

25 DL lactide, containing triethanolamine (TEA) (100 mM) and N-vinylpyrrolidone (VP) (0.15%) and then illuminated by exposure to an argon ion laser at 0.5 W/cm² for 15 sec. The nonpolymerized prepolymer mixture in the lumen of the vessel was rinsed away with saline. Human blood was collected from the antecubital vein

30 and was anticoagulated with heparin at 2 units/ml. This blood

5 was perfused through each vessel by a syringe pump at a flow rate corresponding to a wall shear rate of approximately 200/s for 7 min. The vessel was then superficially rinsed in saline and fixed in formaldehyde.

10 The treated vessel did not appear colored or different in color after perfusion compared to its color before perfusion, while the untreated control vessel appeared blood red. Thin segments of each vessel were cut from each vessel, were mounted on end, and were examined by environmental scanning electron microscopy (ESEM). ESEM is performed on hydrated samples in
15 relatively low vacuum. This permits the visualization of the polymer film coating in the swollen and wet state. This is important to obtain measurements that may be readily interpreted, since the polymer film is approximately 95% water. A high degree of thrombosis was readily observed in the control vessel. The
20 lumen of this vessel was narrowed to less than one-third its diameter pre-perfusion by the accumulation of thrombus, as shown in Figure 20A. By contrast, no thrombus could be observed in the lumen of the treated vessel, as shown in Figure 20B. A higher magnification of the vessel wall demonstrated no adherent
25 thrombus. A still higher magnification shows a white structure which is the polymer film, which is different in contrast from the tissue due to differential charging under the electron beam of the ESEM. The film may be seen to be precisely conformed to the shape of the vessel and be approximately 5 - 8 μ m thick.

5 The region of polymerization was restricted to the
neighborhood of the blood vessel wall surface. The
photosensitive dye was adsorbed to the vessel wall. Unbound dye
was rinsed away. The entire lumen was filled with prepolymer,
but upon illumination the gel formation was restricted to the
10 vessel wall where the dye and the prepolymer meet. This
interfacial polymerization process can be conducted to produce
surface adherent layers that vary in thickness from less than 7
 μm to more than 500 μm .

15 The above procedure was performed in 8 control rat
arteries, and 8 treated arteries, with equivalent light
microscopic histological results as described above. As
demonstrated by this study, PEG prepolymers can be polymerized
upon the luminal surface of blood vessels. The immediate effect
of this modification is to reduce the thrombogenicity of an
20 injured blood vessel surface. This has clear utility in
improving the outcome of balloon angioplasty by reducing the
thrombogenicity of the vessel and lesion injured by balloon
dilation. Another effect of this modification is to be reduce
smooth muscle cell hyperplasia. This may be expected for two
25 reasons. First, platelets contain a potent growth factor,
platelet-derived growth factor (PDGF), thought to be involved in
post-angioplasty hyperplasia. The interruption of the delivery
of PDGF itself poses a pharmacological intervention, in that a
"drug" that would have been delivered by the platelets would be

5 prevented from being delivered. Thrombosis results in the
generation of thrombin, which is a known smooth muscle cell
mitogen. The interruption of thrombin generation and delivery to
the vessel wall also poses a pharmacological intervention. There
are other growth factors soluble in plasma which are known to be
10 smooth muscle cell mitogens. The interruption of thrombin
generation and delivery to the vessel wall also poses a
pharmacological intervention. Moreover, there are other growth
factors soluble in plasma which are known to be smooth muscle
cell mitogens. The gel layer is known to present a permselective
15 barrier on the surface of the tissue, and thus the gel layer may
reasonably be expected to reduce hyperplasia after angioplasty.
The inhibition of thrombosis upon the vessel wall may also reduce
the incidence of abrupt reclosure and vasospasm, both of which
occur sometimes following vascular intervention.

20

Example 53

Interfacial Polymerization of Macromers

Inside Blood Vessels to Prevent Thrombosis

Macromer solutions were polymerized interfacially
within previously injured blood vessels *in vivo* to prevent
25 thrombosis. The carotid artery was exposed, and a polyethylene
tube (PE-10) was used to cannulate the exterior carotid artery.
The artery was clamped with fine arterial clamps proximal to the
interior/exterior carotid artery bifurcation and approximately 2

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5 cm distal to the bifurcation. A 1 ml tuberculin syringe was used to rinse the blood from the lumen of the isolated zone by filling and emptying the vessel zone. The vessel was injured by crushing using a hemostat. The isolated zone was filled with a 10 mM solution of eosin Y for 2 minutes, after which it was rinsed and
10 filled with a 20% solution of a macromer in saline with 0.1 mM triethanolamine and 0.15% N-vinyl pyrrolidinone. The macromer consisted of a PEG chain of MW 8,000 daltons, extended on both sides with a lactic acid oligomer of an average degree of polymerization of 5 lactidyl groups, and further acrylated
15 nominally at both ends by reaction with acryloyl chloride. The vessel was illuminated transmurally using an argon ion laser (514 nm) at an intensity of approximately 1 mW/cm² for 5 seconds. Following this, the cannula was removed from the exterior carotid artery and the artery was ligated at the bifurcation. The
20 arterial clamps were removed to permit the resumption of blood flow. Perfusion was allowed for 20 minutes, following which the vessel were again isolated, removed from the body, gently rinsed, fixed, and prepared for light microscopic histological analysis. Using the naked eye, the crushed segments in control animals,
25 which lacked illumination, were red, indicating internal thrombus with entrapped red blood cells. By contrast, no redness was observed at the site of the crush injury in the treated vessels. Histology showed extensive thrombus, fibrin, and entrapped red blood cells in the non-treated vessels. By contrast, no thrombus

5 or fibrin or entrapped red blood cells were observed in the
treated vessels. The procedure was conducted in four control
animals and three treated animals.

This example demonstrates that the polymerization can
be carried out *in situ* in the living animal, that the polymer
10 coating remains adherent to the vessel wall during arterial blood
flow, and that the polymer coating can prevent thrombosis *in vivo*
in non-anticoagulated animals. This approach to treatment has
clear benefits in preventing abrupt reclosure, vasospasm, and
restenosis after intravascular interventional procedures.
15 Moreover, it is more generally applicable to other intraluminal
and open-surface organs to be treated.

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9. The crosslinked biocompatible material of claim 8, wherein the biologically active materials are living cells selected from islet of Langerhans, dopamine secreting cells, crythropoietin secreting cells, nerve growth factor secreting cells, parathyroid cells, or norepinephrine/-metacephalin secreting cells.

10. The crosslinked biocompatible material of claim 8, wherein the biologically active material is a drug

11. A crosslinked biocompatible material comprising: at least one ionically crosslinked component; and at least one covalently crosslinked component is derived from a polyalkylene oxide.

12. The crosslinked biocompatible material of claim 11, wherein the covalently crosslinked component is polyethylene glycol diacrylate.

13. The crosslinked biocompatible material of claim 11, further comprising a biologic encapsulated by the material.

14. The crosslinked biocompatible material of claim 13, wherein the material is effective to provide immunoprotection for the biologic in a physiological environment.

15. The crosslinked biocompatible material of claim 14, wherein the material provides immunoprotection of the biologic when xenotransplanted.

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